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VOLUME LVI NUMBER 3

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
Mount Wilson Observatory of the Carnegie Institution of Washington

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HENRY G. GALE
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OCTOBER 1922

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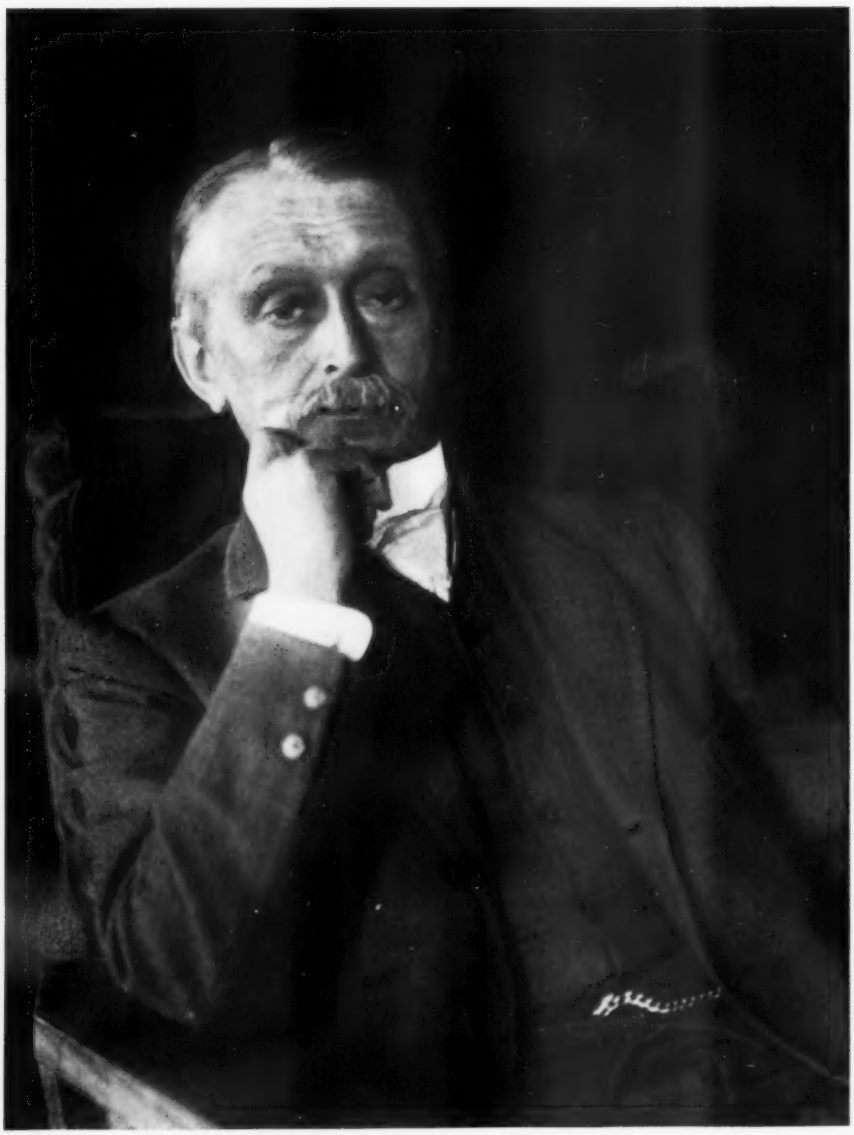

J. C. KAPTEYN

Photograph taken by F. Ellerman in 1914, during Kapteyn's last visit to Mount Wilson.

THE
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J. C. KAPTEYN, 1851–1922

By A. VAN MAANEN

In Amsterdam, on June 18, Jacobus Cornelius Kapteyn, since 1921 retired professor of astronomy and director of the Astronomical Laboratory at Groningen, died at the age of seventy-one years. In him astronomy loses one of its foremost pioneers.

Kapteyn was born January 19, 1851, at Barneveld, a small village where his father had a well-known boarding school. Of the fifteen children of this family several became leaders in the scientific world in Holland. From 1869 to 1875 Kapteyn was a student at the University of Utrecht, where his principal teachers were Buys Ballot and Grinwis, so that it is no wonder that his doctoral thesis was in physics: "Onderzoek der Trillende Platte Vliezen." Just at this time, however, the position of observer at the Leiden Observatory was vacant, and Kapteyn applied for and obtained the position. By this accidental circumstance astronomy secured the privilege of counting Kapteyn as one of its workers and before long as one of its foremost leaders. His ability was soon recognized, and at the age of twenty-seven, which for Holland is extremely young, he was appointed full professor in astronomy at the University of Groningen. On entering office, February 20, 1878, his opening address had as subject: "The Parallax of the Fixed Stars."

The problem of the stellar distances was naturally of first importance to him, whose ideal was to throw some light on the structure of the universe. We do not know when this idea began to ripen in Kapteyn's mind, but it probably dates from the time that he decided to devote his life to astronomy. And no better man could be found to push astronomy ahead along these lines, because Kapteyn had two qualities which were needed for such investigations: he could grasp a great problem and at the same time both could and was willing to devote much time to essential details. These two qualities show up through all his life and we see him, never losing view of the greatest of astronomical problems, the structure of the universe, and at the same time working with painstaking assiduity to develop and improve the methods of securing the necessary data. Of this part of his work no better example can be given than the succession of new methods that he developed to obtain stellar distances. In 1882 the parallaxes of only thirty-four stars were known, the best results being due to heliometer observations, especially by Gill and Elkin at the Cape of Good Hope.

When Kapteyn came to Groningen his appointment was to the professorship in astronomy, calculus of probabilities, and theoretical mechanics, but he found no observatory at his disposal. Good mathematician as Kapteyn was, his heart was drawn more toward the practical side of his science, and during the first years in Groningen he tried hard to secure funds for an observatory, with a six-inch heliometer as its principal instrument. In the beginning his efforts seemed to promise success, and ground for the observatory was bought a little outside of the city, but funds for the erection of the buildings were not forthcoming until many years later, by which time Kapteyn in his unique astronomical laboratory had founded an establishment which satisfied, better than an observatory could have done, the needs of this wonderful combination of the practical and the theoretical astronomer.

Lack of an opportunity for observational work was, however, keenly felt by Kapteyn during the early years of his professorship, and he requested Professor H. G. van de Sande Bakhuyzen to let him use the meridian circle of the Leiden Observatory during his vacations. The request was granted and Kapteyn planned a care-

ful program for the observation of stellar parallaxes; he introduced the differential method of observations in right-ascension, thus deriving parallaxes for fifteen stars, which in accuracy competed with those yielded by the heliometer, while the observations required less time. His thorough discussion of the method and of these observations in Volume VII of the *Annals of the Leiden Observatory* is one of the many contributions from his hand which will be recorded among the classics of astronomy.

But it was clear that for a solution of his great problem parallaxes must be determined more rapidly. In 1889, at the conference of the Carte du Ciel, Kapteyn outlined an ingenious scheme for measuring the parallaxes of a large number of stars by means of photography. The plan is extremely simple in theory: on the same plate three exposures are made at the epoch of maximum parallactic displacement; half a year later, at the minimum, six other exposures are made on the same plate, and three again at the following maximum; after development the plate shows twelve images of each star which in practice are arranged as follows:

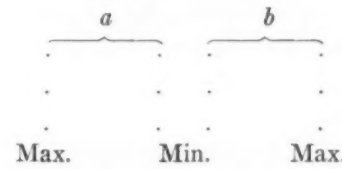


FIG. 1.—Arrangement of exposures for the determination of stellar parallaxes according to Kapteyn's plan.

The distances *a* and *b* are then measured and reduced by a simple process; and yield, with respect to the mean parallax of all the stars measured, the parallax of every star visible on the plates. The method was put into practice by Kapteyn and Donner and the first results were published in 1900 as Number 1 of the *Publications of the Astronomical Laboratory at Groningen*, a remarkable series of publications which has contributed much to the development of astronomy in the last twenty years.

While similar results for different fields, mostly in collaboration with De Sitter, appear in the *Groningen Publications*, we soon perceive a change in his policy of attack on the general problem. The

change from parallaxes to proper motion, however, is more apparent than real, and is founded on the practical fact, that by using the proper motions we can base the parallaxes on the ever increasing base line of the sun's motion through space, and on the theoretical fact, that for the structure of the universe it is not at all necessary to know the distances of individual stars, but the mean distances of groups of stars for different magnitude, spectral type, and galactic latitude. The problem has two requirements: an accurate determination of the sun's motion through space and a knowledge of the distribution of proper motion for an increasingly great number of fainter and fainter stars. Along both lines the *Groningen Publications* reveal how much Kapteyn advanced our knowledge. And it is in just such work as this that Kapteyn's double aptitude for recognizing great problems and at the same time perceiving the practical difficulties, was of the greatest usefulness. Kapteyn would work out a new method which, with the proper material, would give the desired results; but he would at the same time also apply his method to the material available, even when it was scanty and likely to yield only defective results. This, however, had the advantage of showing at once where the method itself could be improved and what data would be most needed. We see him follow this means of attack in all his problems, by successive steps coming ever closer to the laws governing the structure of the universe.

Incidentally the investigations on proper motion led Kapteyn to his discovery of the two star streams, which, rightly, was recently selected by Eddington as one of the five greatest astronomical events of the last hundred years, a discovery which has revolutionized our ideas of the structure of the universe. In deriving the solar motion Kapteyn was struck by the divergency of the results of former investigators. In these researches it was usually assumed that the *motus peculiaris* of the stars was at random, a natural hypothesis, since with the enormous distances of the stars from one another it was difficult to see why there should be any relation between the individual motions of different stars. Yet stars moving together in pairs or even in large groups were known. As early as 1896, however, Kapteyn had noticed that the distribution of motion was not at random, but it was not until 1904 that he showed that there is a fundamental peculiarity in these motions and that

they are not moving even approximately in a haphazard way. Instead of moving in all directions, as a random distribution would require, the stars tend to move in two preferential directions. That this tendency was so long overlooked by those who were working on a determination of the solar motion is principally due to the fact that they used the mean motions of all the stars in certain parts of the sky. Kapteyn, however, went to work in a different way, plotting the proper motions for limited regions of the sky. If for convenience' sake we assume all the stars in a certain region to be located in the same point S of the sphere, then with a random distribution of the *motus peculiaris* alone, we find about the same number and about the same total motion in each direction. A motion of the observer, such as we have as a result of the sun's motion through space, will add to each star a parallactic motion in the direction of the antapex. While this of course will disturb the symmetry of the motions around the point S, we still will have bilateral symmetry, the line of symmetry evidently passing through the point S and the apex. This evident condition of bilateral symmetry would probably furnish the best means of determining the apex, as these lines of symmetry for the different parts of the sky must all intersect in two points, the apex and the antapex. In applying this idea to the proper motions of about 2400 Bradley stars, divided into twenty-eight regions, Kapteyn derived the distribution of the proper motions corresponding to the center of the areas. The whole of the material was thus embodied in twenty-eight figures, like those in Figure 2, each of which shows at a glance the distribution of the proper motions for one particular region of the sky. This Figure 2 is the same as the one shown by Kapteyn at the Cape meeting of the British Association for the Advancement of Science in 1905. Not to overburden the plate, only ten of the twenty-eight regions are included. If the hypothesis of random distribution were true, all these figures should be symmetrical with respect to the line through the center of each field and the apex. It is clear that this is not the case: each figure shows two preferential deviations. Kapteyn showed that the assymetry as shown in the figure can be explained neither by an uncertainty in the precession, nor by systematic errors in the proper motions, nor by an erroneous position of the apex. As all the lines of favored directions for the two sets

seem to converge, approximately, to two points, some 140° apart, the one 7° south of α Orionis, the other a few degrees south of η Sagittarii, Kapteyn came to the conclusion that we must have to do with two star streams, parallel to the lines joining our solar system and the two points mentioned.

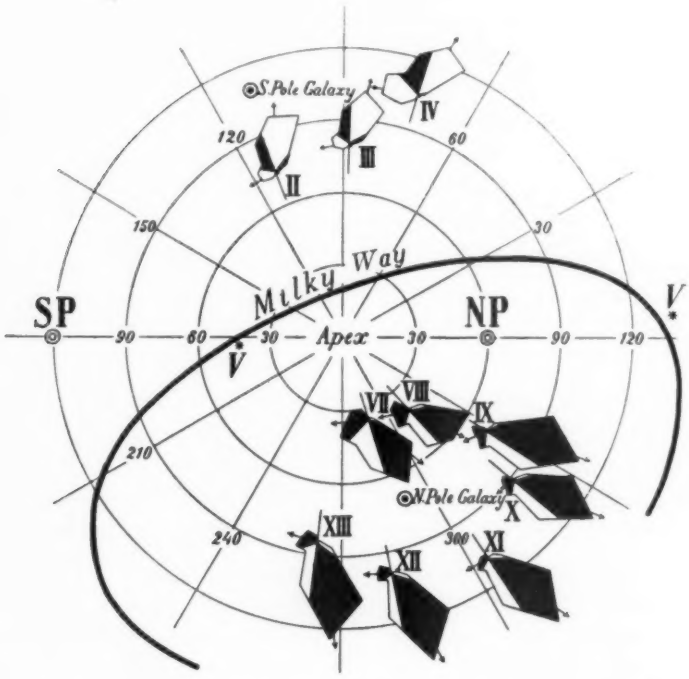


FIG. 2.—Distribution of proper motion in different parts of the sky which led to Kapteyn's discovery of the star-streams.

It is evident that such a discovery as that of the star streams would revolutionize the ideas of the structure of the universe. But at the same time it pointed out the necessity of collecting an increasing amount of data, in order to secure more reliable measures and especially data for the fainter stars. It was clear that the desire for such data could be satisfied only by the thorough co-operation of several institutions according to a well-organized plan. Kapteyn certainly was the right man to start such an organization. Through his work he had come into contact with most of the leading astron-

omers all over the world. His visits to America in 1904 and South Africa in 1905 gave splendid opportunity for discussing his plans with a number of eminent astronomers. In order to enable those who showed an interest in the matter to judge more thoroughly of the details, Kapteyn worked out a provisional plan; the result was a great deal of discussion and many useful suggestions. In 1906 Kapteyn published his famous *Plan of Selected Areas*. This pamphlet gives briefly but clearly, as only Kapteyn could give it, a program for the further attack on the structure of the universe. It includes not only the general plan but also in careful detail the methods of securing the necessary data: magnitude, proper motion, parallax, class of spectrum, and radial velocities for the stars in 252 well-selected regions. In the first and second reports (1911) Kapteyn was able to announce the formation of a committee to share the responsibility of advancing this plan. Its membership included Gill, Pickering, Hale, Küstner, Schwarzschild, Dyson, Adams, and Kapteyn, and it is sad to state that with Kapteyn one-half of its members have already gone forever. Yet the whole astronomical world is so convinced of the need of such a co-operative plan that it will undoubtedly be continued.

Next to the motions of the stars, their distribution in space interested Kapteyn most keenly. In this connection he derived the two well-known laws: the density-law and the luminosity-law, the former giving the density of stars per unit of volume and the change in the density with distance from the sun, and the latter, the percentage of stars equal in luminosity to the sun, and of those 10 times, 100 times, etc., as bright or as faint. Both are statistical laws; they do not give the distance and brightness of the individual stars, but how many stars there are at a certain distance and of a certain brightness. By successive steps these researches led Kapteyn to a conception of the distribution of the stars in space; they indicate that the stars are contained in a nearly ellipsoidal universe with an axial ratio of 5.1 with a decrease in the density away from the center and with the sun at a distance of about 650 parsecs from the center. In his last long paper on the subject, which with the modesty of the really great, was called "A First Attempt at a Theory of the Arrangement and Motion of the Sidereal System," Kapteyn had the satisfaction of giving a beautiful exposition of his life-work.

If a longer life had been granted to him, undoubtedly we would have seen him elaborate his beloved subject; yet as it is, it must have been a great satisfaction to him to reach this goal.

At about the time Kapteyn was spending his vacations in Leiden for the purpose of making his determinations of stellar parallaxes, he became acquainted and was soon on terms of warm friendship with the man who was then the leader in practical astronomy, David Gill, director of the observatory at the Cape of Good Hope. The story of the *Cape Photographic Durchmusterung* is well known to every astronomer. The difficulties met by Gill and Kapteyn would have disheartened most men. Kapteyn's famous letter of 1886 to Gill, offering his help in the following words, "However, I think my enthusiasm for the matter will be equal to (say) six or seven years of such work" has been widely quoted. It took about double that time, yet his enthusiasm did not fail, and the *Cape Photographic Durchmusterung* was completed with a thoroughness and accuracy which could be obtained only by two such masters. If we had no other work from his hand, Kapteyn's name would still take an honorable place in astronomical literature and would be mentioned with those of Argelander, Schönfeld, and Gould, names which every astronomer honors with gratitude. Yet in addition to this we have his discovery of the star streams, his plan of selected areas, his founding of the Groningen Astronomical Laboratory, now called "Astronomical Laboratory Kapteyn," which at the recent meeting of the International Astronomical Union, Baillaud duly called one of the three things which in his fifty years of astronomical life had revolutionized his science; and above all we have Kapteyn's investigations on the structure of the universe.

Truly Kapteyn belonged among the few really great men, whose death creates a vacancy which cannot be filled.

It seems superficial to enumerate here the many honors bestowed on him during his life. For completeness, however, we must mention them: Kapteyn received the honorary degree of D.Sc. from the Cape of Good Hope; of D.Sc. from Harvard University; of LL.D. from Edinburgh; he received the gold medal of the Royal Astronomical Society, the Watson and the Bruce medals and the prix de Pontécoulant; he was chevalier of the Legion of Honor of France, of

the Netherlands Lion; he had the order "Pour le Mérite," and was commander in the Dutch order of Oranje-Nassau. Kapteyn was elected a member or associate of the following academies: Royal Astronomical Society, American Philosophical Society, National Academy of Sciences of Washington, Imperial Academy of St. Petersburg, Royal Academy of Dublin, Royal Academy of Edinburgh, British Association, Royal Swedish Academy, Royal Society of Sciences of Upsala, American Society, the Academy of Sciences in Paris, the Royal Society of London, the Academy of Sciences in Finland, and of the Royal Physical Association in Lund.

All through his life Kapteyn made friends; when he was young, among the older people, when older, among each new generation with which he came in contact. It was not difficult to become his friend; he saw always the best qualities in every person, the rest did not exist for him. There was always an atmosphere of happiness around him, in his daily life as well as in the scientific assemblies, where he was the center of gravity. His departure will be keenly felt in the astronomical world, but not there alone: many others will mourn the ending of this noble and happy life.

Especially in America, Kapteyn had numerous friends. From 1908 to 1914 he came to this country every summer to spend a few months at the Mount Wilson Observatory, of which institution he was Research Associate. Kapteyn and Mrs. Kapteyn thoroughly enjoyed their American trips, and these visits were no less appreciated by all with whom they came in contact.

Mrs. Kapteyn was born Catharina Elisabeth Kalshoven, and they were married in 1879. Their married life was singularly happy, and she has been devoted to the welfare of her husband and children, two daughters and a son: Jacoba Cornelia, wife of Professor W. Noordenbos, of Amsterdam; Henriette, wife of Professor E. Hertzsprung, of Leiden; and Gerrit Jacobus Kapteyn, who is a mining engineer.

How truly are his characteristics described by his friend Huizenga in the July number of the *Gids:* "When the right biographer for Kapteyn is found, the 'Life of Kapteyn' will be one of the most beautiful books that can be written."

MOUNT WILSON OBSERVATORY
PASADENA, CALIFORNIA
August 1922

VISIBLE AND INFRA-RED RADIATION OF HYDROGEN

By FREDERICK SUMNER BRACKETT

ABSTRACT

Infra-red spectrum of hydrogen to 4.5 μ.—The radiation from the central section of a long discharge tube, such as the one used by Wood to extend the Balmer series to the twentieth term, was analyzed by means of a rock-salt prism spectrometer, and readings were taken with an extremely sensitive vacuum thermo-junction. Besides some unidentified lines (Fig. 1), *five members of the Paschen series*, three of them new, were observed at the wave-lengths corresponding to the formula $\nu = N(1/3^2 - 1/m^2)$, where $m = 4, 5, 6, 7, 8$; also the *first two members of a new series* corresponding to $\nu = N(1/4^2 - 1/m^2)$, where $m = 5, 6$, were observed at 4.05 and 2.63 μ. According to the Bohr theory these two series are due to electrons falling from outer orbits into the third orbit and fourth orbit respectively.

Variation of the relative intensity of Balmer and Paschen series lines of hydrogen with the current.—For the long discharge tube used, the first Paschen line was found to increase in intensity more rapidly than $H\alpha$, as the current was increased from one-ninth to one-half ampere through a section 7 mm in diameter.

INTRODUCTION

Two lines due to hydrogen were observed by Paschen[1] at the wave-lengths 18,751 A and 12,818 A. According to the Bohr theory these are due to an electron falling into the third from the fourth and fifth stable orbits in the hydrogen atom.

In view of the very low intensities of these spectral lines observed by Paschen, the detection of a series due to an electron falling into the fourth from orbits of greater quantum number has been considered improbable. In fact the lines mentioned above, forming the first two members of the Paschen series, were so faint that in order to observe them Paschen found it necessary to set the spectrograph in the correct position according to the wave-length predicted by Ritz in consequence of his combination principle.

By using a very long hydrogen tube Professor Wood[2] found it possible to abolish the secondary spectrum from the central position of the tube, and photograph the lines of the Balmer series down to the twentieth member. From the standpoint of the Bohr theory, this increase in the intensity of the higher members of the

[1] *Annalen der Physik*, **27**, 537, 1908.

[2] *Proceedings of the Royal Society*, **97**, 455, 1920; *Philosophical Magazine*, **42**, 729, 1921.

Balmer series might be attributed to increasing the probability of transitions between the orbits of higher quantum numbers. That being the case, we should expect an increase in the intensity of lines of other series which are also due to transitions of the electron between orbits of higher quantum numbers.

That this proved to be the case, and to a degree far greater than anticipated, is the essential feature underlying the success of the present investigation.

APPARATUS

The hydrogen tube of pyrex glass, used as the source, was about one meter in length. A central portion 25 cm long was viewed end on through an elbow in the tube. This portion of the tube was 7 mm in diameter (inside dimension). This small-size tubing was also used for a distance of about 10 cm on either side of the portion viewed. The remainder of the tube was made of larger diameter in order to reduce the resistance as much as possible. The electrodes were of thin aluminum foil rolled into hollow cylinders 8 cm long by 2 cm in diameter.

Hydrogen was introduced through a capillary sealed in near one electrode. The tube was exhausted by a Gaede mercury pump, communicating with the tube near the other electrode. During observation the pump was run continuously, the pressure depending upon the balance between the pump and the capillary intake.

Alternating high potential was supplied by a 6600-volt 5-kilowatt transformer operating on a 110-volt, 60-cycle primary circuit. The potential difference applied across the tube was varied by introducing resistance into the primary. The highest current maintained through the tube was a little more than half an ampere.

The dark space about the electrodes was about 3 mm in length, the positive column occupying almost the entire length of the tube. Striation appeared only in the portions of the tube of larger diameter, the central constricted portion being occupied by apparently continuous luminosity. The secondary spectrum was noticeable only near the electrodes. Throughout the greater part of the

tube, the Balmer lines appeared with great brilliancy against a practically black background when the tube was viewed through a direct-vision prism.

The dispersion apparatus was a rock-salt monochromator of the Wadsworth type. Concave mirrors of 60-cm focal length were used for both collimator and telescope. The clear aperture of the prism was about 4 cm in diameter. Light only traversed the prism once, the simple form of apparatus being chosen in order to avoid scattered light. The slit widths were about 1 mm.

The detecting apparatus consisted of a single-junction vacuum thermo-couple, of the type constructed and previously used by Professor Pfund for measurement of stellar radiation. This was connected in series with a d'Arsonval galvonometer of sensibility about 5×10^{-10}.

A scale-distance of three meters was used, giving altogether an arrangement of extreme sensibility.

The light from the second slit was concentrated upon the blackened strip of the thermo-junction by means of a short-focus concave mirror. Both mirror and thermo-junction were protected by an asbestos housing. The leads to the galvanometer were carried through a metal conduit, grounded to prevent electrostatic effects. The galvanometer case, posts, etc., were heavily covered with cotton batting. The stability of this arrangement proved very satisfactory, deflections being reliable to 0.1 mm.

RESULTS

Part I. Distribution of intensity.—Figure 1 shows the distribution of intensity of radiation due to hydrogen in the infra-red between wave-lengths 0.5 μ and 4.5 μ.

In this diagram intensities have been plotted as the ordinates measured in millimeters of deflection of the galvanometer. It has been shown that intensities are proportional to galvanometer deflections for this thermo-couple for small deflections such as are obtained here. The abscissae are simply micrometer turns of the monochromator. The dispersion-curve based on five known points of the monochromator is shown superposed. Its ordinates

are wave-lengths in microns indicated on the right. In order to read the wave-length of any point on the intensity-curve it is

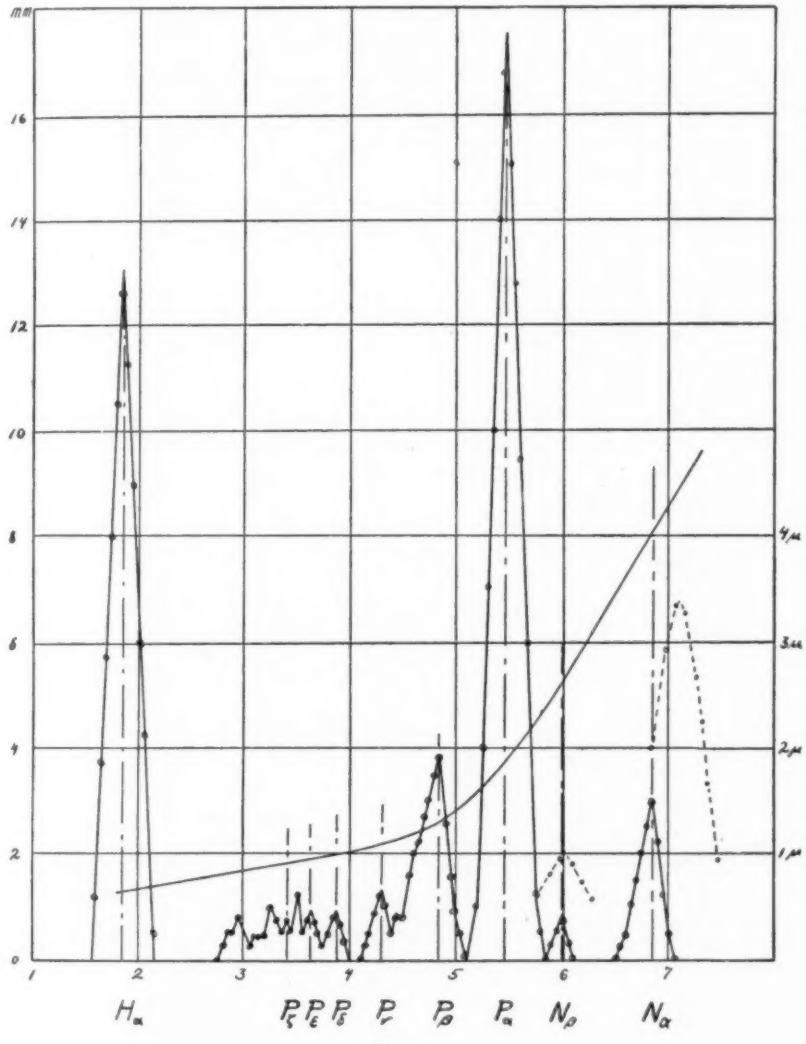


FIG. 1

merely necessary to find the point of the dispersion-curve having the same abscissa and read its ordinate at the right.

The maximum occurring at $4.05 \pm .03\ \mu$ and the second one at $2.63 \pm .02\ \mu$ are the first two members of a new series predicted from the Bohr theory by the formula

$$1/\lambda = 109{,}677.7\ (1/4^2 - 1/m^2);\ m = 5.6.$$

That is, they are attributed to an electron falling into the fourth from the fifth and sixth stable orbits of the hydrogen atom according to Bohr's model.

The largest maximum occurring at $1.88\ \mu$ is the first line of the Paschen series. It will be noted that it has an intensity greater than Hα (the last maximum on the left) in the ratio of about 4 to 3. The next four maxima are the next four members of the Paschen series.

The identity of the succeeding maxima is uncertain. Other lines are certainly present which do not belong to the Paschen series. The second maximum is probably Pζ.

These lines of the Paschen series are predicted from the Bohr theory by the formula

$$1/\lambda = 109{,}677.7\ (1/3^2 - 1/m^2);\ m = 4,\ 5,\ 6,\ 7,\ 8,\ (9),\ 10.$$

Line	Observed Wave-Length	Calculated Wave-Length
Pα	($1.88\ \mu$)	$1.875\ \mu$
Pβ	($1.28\ \mu$)	$1.282\ \mu$
Pν	$1.09 \pm .01\ \mu$	$1.094\ \mu$
Pδ	$1.01 \pm .01\ \mu$	$1.005\ \mu$
Pϵ	$0.95 \pm .01\ \mu$	$0.955\ \mu$

The dispersion-curve from which the wave-lengths have been determined is based upon five known points: $4.4\ \mu$ and $2.7\ \mu$ of the Bunsen flame (shown by dotted lines—scale reduced 100 times) and the three known hydrogen lines Pα, Pβ, and Hα. The values thus obtained should be quite satisfactory for purposes of identification, but of course have no great value from the standpoint of accurate wave-length measurement.

In view of the great intensity of the Paschen lines it is not surprising that many lines were readily observed which under ordinary conditions of excitation would not be detected. The

readings shown on Figure 1 were taken in sequence, without setting upon known wave-lengths. The identity of the maxima was not realized until the dispersion-curve was later plotted.

Part II. Variation of intensity with current.—As it was noticed that the appearance of the tube changed decidedly with change in current, a set of intensity readings was taken on the first lines of three series—the Balmer, the Paschen, and the new series, when the current through the tube was varied from one-sixth of an ampere to over one-half an ampere. The curves obtained are shown in Figure 2.

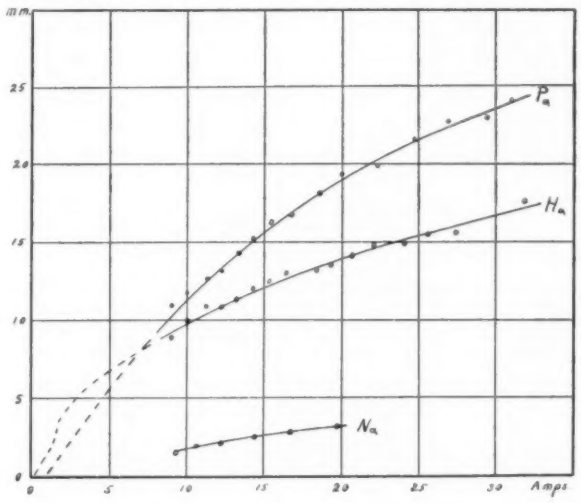


FIG. 2

The ordinates are intensities in millimeter deflections of the galvanometer, and the abscissae are current strengths through the primary of the transformer. The current through the tube is found with sufficient accuracy by dividing by 60. Readings on *a* of the new series are not shown for currents greater than 20 amperes primary, one-third ampere secondary, as radiation from the glass tube itself rendered them uncertain. No such effect was observed for lower currents or wave-lengths less than 3.5 μ. As a further precaution the tube was run only during the time of actual reading.

From this diagram, Figure 2, it will be noticed that although all three lines increase in intensity with increasing current, Pα increases by far the most rapidly. Further readings (dotted portion of the curve) showed that at currents less than 7 amperes primary (about one-ninth ampere secondary) Hα was more intense than Pα.

At a current of 23 amperes through the primary we have the ratio of the intensity of Pα to Hα a little more than 4 to 3. According to the Bohr theory the energy lost by an electron undergoing transition from the fourth to the third orbit of the hydrogen atom will be

$$W_{P\alpha}=(1/3^2-1/4^2)\,Nh=7/144\,Nh,$$

while that lost in transition from the third to the second orbit would be

$$W_{H\alpha}=(1/2^2-1/3^2)\,Nh=20/144\,Nh,$$
$$W_{P\alpha}/W_{H\alpha}=7/20.$$

So the energy given out by an electron in transition from the fourth to the third orbit is only seven-twentieths of that given out by an electron falling from the third to the second orbit. Hence, in order to have Pα more intense than Hα in the ratio 4:3, there must be more atoms radiating Pα than Hα in the ratio of

$$\frac{4\times 20}{3\times 7}=\frac{80}{21}.$$

In view of the greater stability of the orbits of smaller quantum number and taking into account the principle of selection, we see that this is incompatible with what would be expected if radiation were resulting only from recombination of the atom and electron after ionization. We must therefore conclude that to a large extent radiation in such a long hydrogen tube arises from inelastic collision without ionization. In such a case we may have an abnormal concentration of energy in certain wave-lengths which would not be the case for recombination after ionization, inasmuch as the probability of an electron stopping in an orbit of high quantum number is much greater, where it is simply ejected to that orbit or one of slightly greater quantum number, than in the case where it

is returning from ∞. This no doubt explains to a large extent the peculiar characteristics of the "long hydrogen tube," both in regard to the unusual intensity of the infra-red lines and also the higher members of the Balmer series.

All atoms which contribute to the radiation of the first Paschen line are left necessarily with the electron in the third orbit, whence it must proceed either to the second or the first orbit unless it is ejected to some orbit of greater quantum number by inelastic collision. Since considerably less than one-fourth of these atoms contribute to the radiation of Hα, we must conclude either that the second member of the Lyman series is radiated with great intensity, or that there must be multiple collisions to a large extent in such a tube.

It should be noticed that the higher members of the Paschen series occur in a region readily studied by photographic methods, plates hypersensitized by means of dicyanin being sensitive to 1.0 μ. This work will be carried out in the near future.

CONCLUSION

1. The first two lines of a new series have been observed at wave-lengths $4.05 \pm .03$ μ and $2.63 \pm .02$ μ, due, according to Bohr's theory, to an electron falling into the fourth from the fifth and sixth rings of the hydrogen atom.

2. Three and probably four additional members of the Paschen series have been observed.

3. The first Paschen line is more intense than Hα in the ratio 4:3 under the conditions prevailing in the long tube for great current densities.

In this work I have been much indebted to Dr. Pfund, who proposed the problem and constructed the thermo-junction, the remarkable sensibility of which rendered the work possible.

It gives me great pleasure to express my appreciation to him, to Professor Wood for his interest and many suggestions, and to Dr. Ames for his generous support.

JOHNS HOPKINS UNIVERSITY
June 1922

A GENERAL STUDY OF DIFFUSE GALACTIC NEBULAE[1]

By EDWIN HUBBLE

ABSTRACT

Suggested classification of nebulae.—Since the time of the Herschels, photography and spectroscopy have revolutionized the study of nebulae. The classification here suggested is based upon the fundamental differences between galactic and non-galactic nebulae. Galactic nebulae are subdivided into planetary and diffuse (luminous and dark), and non-galactic into spiral, elongated (spindle and ovate), globular, and irregular. The characteristics of each are discussed. The belief expressed by Curtis that all non-galactic nebulae are spirals is not justified by the facts.

Distribution of diffuse nebulae.—As shown in Figure 1 these nebulae are concentrated along two belts. One is the Milky Way and the other is approximately the belt of bright helium stars which defines the local cluster. Very few seem to occur in the vast regions between the Milky Way clouds and the local cluster.

Spectral characteristics of galactic nebulae and of associated stars.—(1) *Diffuse nebulae.* Some preliminary results, obtained with slitless spectrographs of various dispersions, are presented for sixty-two nebulae outside the Magellanic clouds, including the twenty-one whose spectra were previously known. They fall into two groups (Tables I and II): Group 1 contains thirty-three, giving predominantly continuous or absorption spectra; and Group 2, twenty-nine, giving predominantly emission spectra. The members of the "continuous" group have generally a smooth, cloudy structure and most of them are found in our local cluster, while those of the emission group are more likely to be filamentous and wispy and to lie in the Milky Way clouds. In the emission spectra the N_1 and N_2 lines are much weaker in comparison with $H\beta$ than in spectra of normal planetaries. (2) *Stars associated with diffuse nebulae* have been studied with slit spectrographs attached to the Mt. Wilson reflectors (Tables III and IV). Stars involved in nebulae having continuous spectra are nearly all of type B1 or later; but stars involved in emission nebulae nearly always have spectra earlier than B1, rarely showing any bright lines. (3) *Stars associated with planetary nebulae* show a corresponding relation. In fact, there is a steady progression in type from the Wolf-Rayet stars involved in small planetaries, through those involved in large planetaries, to the stars of types Oe5–Bo associated with extended diffuse nebulae of Group 1 and the stars of type B1 and later associated with diffuse nebulae of Group 2. A detailed discussion shows that, with the exception of the Cygnus loop and perhaps three other difficult or doubtful cases, each galactic nebula has associated with it one or more stars of a type conformable to its own spectral type. (4) This definite relation between the spectra of the nebulae and of the associated stars suggests that the *source of luminosity of the nebulae* is the radiation from those stars. According to this view, the nebulosity has no intrinsic luminosity but either is excited to emission by light from a star of earlier type or merely reflects light from a star of later type. From a consideration of the nebulosity around Rigel it appears that this luminosity may be excited at a distance of twenty light-years.

Nature of diffuse nebulosity.—From the foregoing results the nebulosity seems to consist of clouds of matter, molecules, dust, or perhaps larger particles, not hot enough to be self-luminous, but visible because of light excited by or reflected from involved or neighboring stars. Nebulae with continuous spectra seem usually more opaque than those giving emission spectra. Whether the association of such stars and nebulae is permanent or temporary is not yet known, but may be determined by studies of the radial velocities.

[1] *Contributions from the Mount Wilson Observatory*, No. 241.

Uncatalogued nebulae.—*Five* are listed: Table I, Nos. 4, 5, 15, and 21; Table II, No. 15. The third is a bright cometary nebula with a thirteenth-magnitude star at the apex; $\alpha = 6^h 3^m 1$; $\delta = +18°42'$ (1920).

Radial velocities of five stars associated with galactic nebulae.—Results are given for stars associated with N.G.C. 1514, 6514, 6523, and 7635. Of these B.D. $-23°13804$ and Boss 4560 are *binaries*.

CLASSIFICATION OF NEBULAE

The classification of nebulae from visual observations was of necessity based upon resolvability, brightness, size, and form. Thus Sir William Herschel distinguished between clusters and nebulae and devised, for the latter, three classes for brightness, a fourth for definite form, and a fifth for extra large size. It is true that he mentioned in his discussions the terms "milky nebulosity," "nebulous stars," and "stellar nebulae"; that his penetrating genius recognized the existence of nebulous fluid in the nebulous stars and probably in such milky nebulae as the great one in Orion, in contrast to the stellar nebulae or burred stars which he considered as distant clusters; that, in short, he did realize a distinction between planetaries and diffuse nebulae on the one hand and on the other the non-galactic nebulae; but throughout his researches he adhered strictly in catalogues and descriptions to the five classes: bright, faint, very faint, small with definite borders, and exceedingly large. This formal classification was elaborated by the simple system of abbreviation, still in general use, by which each object was described in considerable detail.

Sir John Herschel developed his father's system. His generation had discarded Sir William's idea of a nebulous fluid, as a direct result of the resolution of nebula after nebula by Lord Rosse's great mirrors. Even the Orion nebula, last stronghold of the nebulous fluid advocates, had been announced as resolved by the Parsonstown observers, and the central star in N.G.C. 1514, the great brightness of which as compared to the surrounding nebulosity had led Sir William to his belief in a nebulous fluid, was being explained not as a single star but as an exceptionally compact cluster of stars.

This state of affairs led Sir John Herschel[1] to avoid the discussion of physical distinctions among nebulae and to elaborate his

[1] *Cape Results* (1847), p. 137.

father's formal classification in an ingenious manner. All nebulous objects were divided into regular and irregular, and the latter alone into nebulae and clusters, according to the difficulty of resolving them.

Regular nebulous objects were classified according to magnitude, brightness, roundness, condensation, and resolvability, with five degrees of each expressed by numbers. Thus a bright globular cluster would be 22322, meaning large, bright, round, condensed, and resolved. A small spindle might be classed as 43435, small, faint, elongated, considerably brighter center, irresolvable.

Irregular nebulae were classed as subregular, compact, branching, convoluted, cellular, fissured, and cometic, although Sir John remarks that these objects are so diverse that each one might well represent a separate class. Each subdivision was arranged in five orders of magnitude and brightness.

Here again is a tendency to distinguish between galactic and non-galactic objects, for the regular nebulae, although including the planetaries, for the most part make up the non-galactic nebulae, while the irregular are in general galactic nebulae.

This system of classification did not win a general acceptance because of its very elaboration and also because of the subsequent introduction of spectroscopy and photography. The new methods of research revolutionized the study of nebulae and the basis of nebular classification. Sir William Herschel's ideas were restored in part at least, for the existence of nebulous fluid in the form of gas or dust clouds in the planetaries and diffuse nebulae became a recognized fact. The old question of resolvability is now restricted to spirals and the kindred small non-galactic objects. There has slowly emerged a general recognition of the fundamental difference, hinted at by the Herschels, between planetaries and diffuse galactic nebulosities and the objects, spirals and others, that swarm in regions of high galactic latitude.

Curtis has expressed this new point of view by dividing nebulae into three classes—planetaries, diffuse, and spirals.[1] In explanation of the term "spiral" he states: "It is my belief that all the many thousands of nebulae not definitely to be classed as diffuse or plane-

[1] *Adolfo Stahl Lectures* (1919), p. 98.

taries are true spirals and that the very minute spirals appear as textureless discs or ovals solely because of their small (apparent) size."[1]

His argument for the truly spiral nature of all these non-galactic nebulae is this: "Were the great Nebula in Andromeda situated five hundred times as far away as at present, it would appear as a structureless oval 0′.2 long, with very bright center, and not to be distinguished from the thousands of very small round or oval nebulae found wherever spirals are found. There is an unbroken progression from such minute objects up to the great Nebula in Andromeda itself. I see no reason to believe that these very small nebulae are of a different type from their larger neighbors."[2]

This argument is a daring extrapolation and is not justified by our present knowledge of nebular forms. Only a few hundred of the thousands of nebulae photographed show distinct traces of spiral arms. Objects of the most diverse forms, were they removed to the proper distances, would appear as faint "textureless discs or ovals" on the photographic plate. Curtis' extrapolation is not warranted unless all the larger objects examined show positive evidence in favor of, or at least no evidence against, a truly spiral structure.

Now the well-known irregular nebulae, N.G.C. 2366, 4214, and 4449, are unquestionably non-galactic and of considerable size, but by no stretch of the imagination, nor by any orientation, can these objects be termed true spirals. Yet many true spirals are recognized, which have diameters a tenth and less the diameters of these nebulae. It is possible of course to consider the irregular objects as rare exceptions to the general run of non-galactic nebulae.

Stronger evidence of non-spiral forms is found in a class of objects which may be termed globular nebulae. Some of the brighter examples of this type are M 49, 60, 84, 86, and 87, which average about two minutes of arc in diameter.[3] Repeated attempts with the 100-inch reflector under excellent observing conditions, using exposure times from one minute to nine hours, have failed to show any trace or suggestion of spiral structure in the objects mentioned. M 32, the smaller and brighter companion of the

[1] *Publications of the Lick Observatory*, 13, 12, 1918. [2] *Loc. cit.*

[3] M 60 and M 87 are shown in Plate III.

Andromeda nebula, is a slightly elongated variant of the globular type which also fails to show spiral characteristics under the resolving power of the 100-inch reflector. A long list could be compiled of non-galactic nebulae with diameters over a minute of arc which show no indication of spiral structure under the highest resolving power available. The number is comparable to that of the known spirals. A progression in size of these globular objects can readily be formed running from diameters of over two minutes of arc down to the limits of photographic plates. Toward the lower end of the sequence they merge into the spirals so that the two types become completely indistinguishable (Plate III).

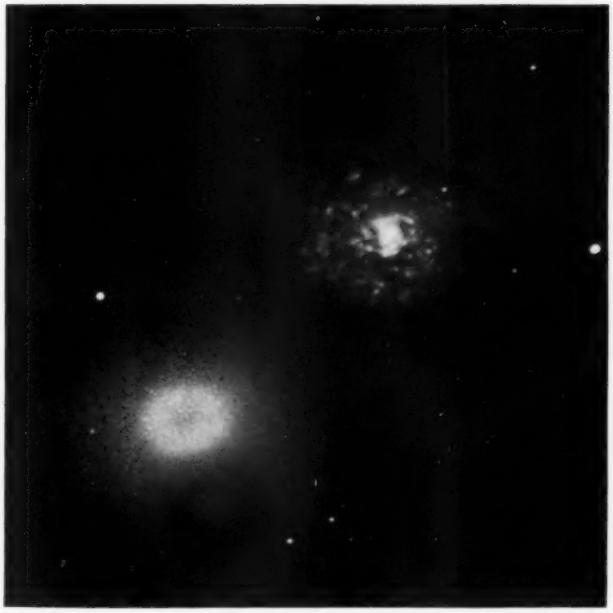
These globular nebulae may be considered as belonging to the same family as the spirals—distribution, velocities, spectra, non-stellar nuclei, and symmetry of form suggest as much—but there is no shadow of evidence for calling them spirals in fact.

Curtis' classification, however, is easily the most significant that has been proposed up to date, and with some modifications would be acceptable as a system the general use of which should be urged. There appears to be a fundamental distinction between galactic and non-galactic nebulae. This does not mean that the latter class must be considered as "outside" our galaxy, but that its members tend to avoid the galactic plane and to concentrate in high galactic latitudes. The distinction seems to be fundamental in a physical sense as well as in distribution. Galactic nebulae are in general associated with stars; even the dark nebulosities are detected by their obscuration of stars. Non-galactic nebulae show no effect on stellar distribution in their neighborhood and have no stars definitely associated with them save those occasional novae which have flared up in a few spirals. The distinction can also be traced in form, texture, velocity, and spectrum, with little if any overlap. In fact, one can say that in no case, except possibly the Magellanic clouds and the similar object N.G.C. 6822, is there any question, from its photographic appearance alone, as to the class to which an individual nebula belongs.

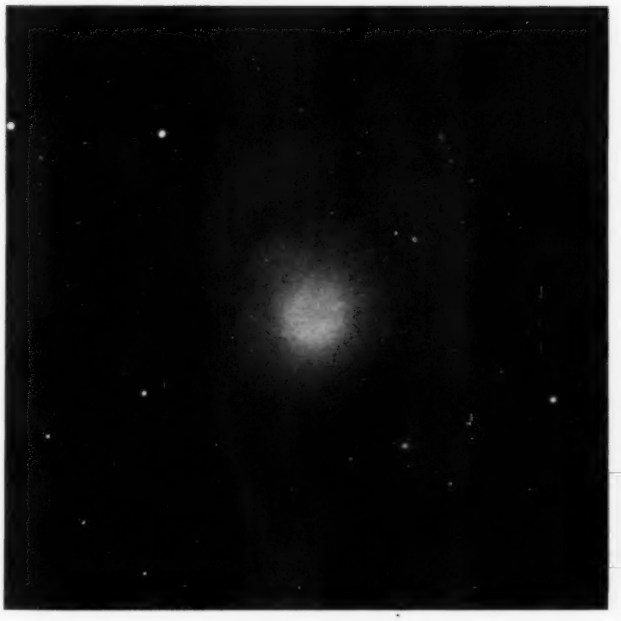
Once this major division is recognized, the subclasses of galactic nebulae follow directly. They are *planetaries* and *diffuse* nebulae. Diffuse nebulae can be divided into luminous and non-luminous

PLATE III

North



a



b

GLOBULAR NEBULAE

a. M 60, N.G.C. 4649 Globular 1 mm = 4″.2
N.G.C. 4647 Spiral
b. M 87, N.G.C. 4486 1 mm = 5″.2

Photographed with the 100-inch Hooker reflector

or dark nebulae. More detailed classification of these groups will depend upon form, spectrum, and relation to stars, and can well be left to special investigators.

Subdivision of non-galactic nebulae is a much more difficult problem. At present and for many years to come their classification must rest solely upon the simple inspection of photographic images, and will be confused by the use of telescopes of widely differing scales and resolving powers. Whatever selection of types is made, longer exposures and higher resolving powers will surely cause a reclassification of many individual nebulae, although the true spiral once recognized as such will maintain its class with all more powerful instruments, and irregular and globular types are not usually subject to change. Only a very low percentage of nebulae, and these the smaller ones, which appear globular with 24-inch apertures, resolve themselves into spirals or reveal ansae with a 100-inch aperture.

Globular nebulae have already been mentioned. The few known *irregular* nebulae are chaotic forms with non-stellar nuclei and coarse granular texture, and with spectra and radial velocities similar to those of the spirals. Examples are N.G.C. 2366, 4214, and 4449. They are easily distinguished from diffuse nebulae by their non-stellar nuclei and their texture, although analogies have sometimes been drawn between these irregular nebulae and the Magellanic clouds.

The gap between *spirals* and *globular* types is filled with the *elongated* nebulae. There are two distinct varieties of these, the one probably spirals on edge and the other akin to globular nebulae. They may be termed, respectively, spindles and ovate. The former, with sharp nuclei and tapering ansae, are familiar to all observers. The latter deserve some further comment. Examples of the ovate type are M 32 and M 59. They are similar to the globular nebulae in all save their elongated forms. Both are to be described as large and bright, yet even the 100-inch under the finest observing conditions with both long and short exposures reveals no trace or suggestion of spirality in either nebula. Whatever their past or future, their present state is not that of true spirals within the limits set by our observational data.

Spindles and ovate types merge into one another with decreasing linear size of the images on the plates, and the resulting confusion detracts from the value of the distinction for small objects or small-scale photographs. As a matter of fact each system of classification that can be devised for non-galactic nebulae will favor a certain range of resolving powers. The present one favors the largest reflectors. It is a compromise between Curtis' generalization and Wolf's specialization.[1]

Some light on the validity of this classification, and a scale for standardizing results from instruments of various dimensions, for statistical purposes at least, can be derived from photographs of rich fields of nebulae made with telescopes of different apertures and equivalent focal ratios, and with one telescope and differing exposure times. Classification of the nebulae for each exposure will indicate the percentage of objects of each type which are changed from one type to another with increasing exposure and resolving power. Preliminary investigations along this line have already been made, apertures from 10 to 100 inches being used.

The classification proposed for general use, together with typical objects for each class, is as follows:

	Examples
I. Galactic nebulae	
1. Planetary	N.G.C. 7662
2. Diffuse	
a) Luminous	N.G.C. 1976
b) Dark	Barnard 86
II. Non-galactic nebulae	
1. Spiral	M 101 (N.G.C. 5457, 8)
2. Elongated	
a) Spindle	HV 24 (N.G.C. 4565)
b) Ovate	M 59 (N.G.C. 4621)
3. Globular	M 87 (N.G.C. 4486)
4. Irregular	N.G.C. 2366

DISTRIBUTION OF GALACTIC NEBULAE

The distribution, spectra, and radial velocities of planetaries are now well known, due largely to the investigations carried out at the Lick Observatory. Large planetaries are distributed

[1] Wolf's classification of non-galactic nebulae is to be found in *Publicationen des Astrophysicalischen Instituts Königstuhl-Heidelberg*, Band III, No. 5, 1909.

more or less uniformly over the sky, while the small ones concentrate sharply along the Milky Way and are especially numerous between eighteen and twenty hours of right ascension. It is reasonable to suppose that the apparent diameters and nuclear magnitudes are rough indications of distance and that, when real distributions are determined, the vertical deviations from the galactic plane will prove to be relatively small. Radial velocities of ninety-six planetaries corrected for the solar motion average 30 km or about five times the average for B stars. Their spectra are almost purely emission, the continuous spectrum being entirely negligible except for the region on the more refrangible side of the head of the hydrogen series. The ratio of intensities between the N_1, N_2, and $H\beta$ images is 10:3:1, with few exceptions.

Much less is known concerning the diffuse galactic nebulae. Their distribution in the sky is certainly not a simple concentration along the galactic plane. Figure 1 represents the distribution in galactic co-ordinates of all objects of this class, excepting those between galactic longitudes 200° and 300° which are too far south to be observed from Mount Wilson. Two distinct belts are defined —the Milky Way, and a belt inclined at about 20° to the Milky Way. This latter belt has approximately the same nodal points as those of the bright helium stars, although the inclination is considerably greater than that usually given for the stars. The data are not sufficient to determine a value for the dip.

Such a distribution emphasizes the relation between diffuse nebulosity and early type stars. The high inclination of the nebular belt suggests that these objects are comparable in distance with the brightest of the B stars and for the most part lie on the inner side of the ring. There is some evidence that the diffuse nebulae are concentrated in the local cluster and in the Milky Way clouds, and that vast regions between the two are practically devoid of nebulae. If this were not the case, we should expect to find the gaps between the two belts more generally filled, and also a greater dispersion among the galactic nebulae. Perhaps the strongest point in favor of such a distribution is the absence of nebulae with large positive galactic latitudes between longitudes 80° and 200°. In all these 120 degrees of longitude only one diffuse nebula

has a latitude greater than +2°. This object is B.D. +23°1301 at +3°.5, announced by Barnard as a nebulous star. The spectrum is B9, photo-visual magnitude 7.0, and hence it is probably relatively near. The greatest deviation from either plane is in the isolated group of dark and luminous nebulosity in Corona Australis, which includes the variable nebula, N.G.C. 6729. The distance of the group is of the order of one hundred parsecs,[1] so that it lies well within the local cluster, and its anomalous position in the sky must be due to perspective. The vertical distance from the galactic plane is about thirty parsecs.

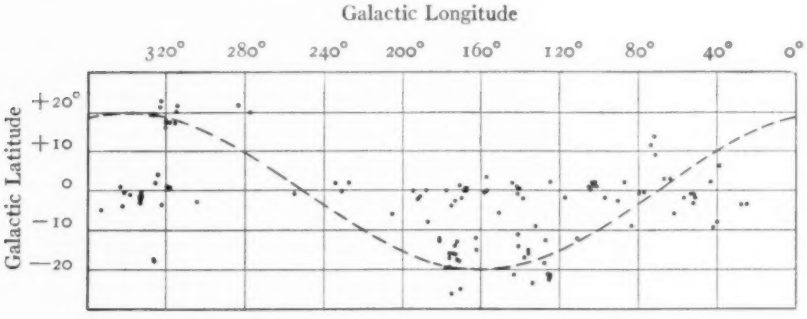


FIG. 1.—Distribution of diffuse nebulae in galactic co-ordinates

There is a decided tendency for diffuse nebulae to cluster. This is more pronounced among nebulae with predominantly continuous spectra than among those with emission spectra, and usually is accompanied by extensive dark nebulosity. Dark nebulae tend to follow the double distribution, although the scattering is greater and the gaps between the two belts are more generally filled than is the case with the luminous diffuse nebulae.

SPECTRA OF DIFFUSE NEBULOSITIES

Published results list emission spectra for thirteen diffuse nebulae as against continuous or absorption spectra for eight.[2]

[1] A distance of three hundred light-years is derived from the luminosity law applied to nebulous stars in the obscured areas, and from movements of luminosity in the nebula N.G.C. 6729 on the assumption that such movements have the velocity of light.

[2] This leaves out of consideration the nebulae in the Magellanic clouds.

This has somehow led to a presumption that an emission spectrum is a general characteristic of diffuse galactic nebulae.

Slit spectrograms of such faint objects will accumulate so slowly that it seems worth while to publish now some results from a preliminary survey with slitless spectrographs. Such instruments readily distinguish spectra which are predominantly emission from those predominantly continuous, although faint emission images on a strong continuous background cannot always be detected. Absorption lines are usually concealed in slitless spectra and the term "absorption spectrum" can be applied in general only to slit spectra. Several such spectra have been reported by Slipher and Pease, so that pure absorption spectra of diffuse nebulosities are as well established in fact as pure emission spectra of others. Indeed, it may be considered as better established, for it is more probable that all bright-line nebular spectra have some faint continuous background than that faint bright lines have been overlooked in absorption spectra of nebulae. The term "emission" will be used in discussing slitless spectra as an equivalent to "bright line" in slit spectra; the term "continuous," where neither bright nor dark lines can be seen; the term "absorption," where dark lines can actually be detected in either slit or slitless spectra. An unbroken series can readily be arranged from the slitless spectrograms, running from emission with no perceptible continuous spectrum to continuous with no emission. There is probably an uncertain number of objects listed as "continuous" in which faint emission images are present and not recognized, but in every case of previously known emission on a continuous background, the slitless spectra show unmistakable irregularities in distribution of density. In view of the uncertainty, however, the method adopted is to list the nebulae as giving predominantly continuous or predominantly emission spectra, and to call attention in notes to combinations of characteristics.

The various instruments employed in the survey are listed below and each is designated by a letter, by which it will be referred to in the course of this paper. It will be noticed that the range in the relation of scale to dispersion is sufficiently wide to accommo-

date itself to nebulae of all sizes. Seed 30 plates were used throughout with exposures ranging from two to nineteen hours.

A. Focal-plane spectrograph with slit removed, attached to 60-inch reflector, primary focus. Collimator and camera lenses about 6-inch focus. Dispersion, $H\beta$ to $H\epsilon = 5.0$ mm.
B. 15° objective prism on 10-inch Cooke astrographic lens, focus 45 inches. $H\beta$ to $H\epsilon = 5.3$ mm.
C. 6° objective prism on 10-inch Cooke lens. $H\beta$ to $H\epsilon = 1.8$ mm.
D. 39° objective prism on 4-inch lens, 7-inch focus, $H\beta$ to $H\epsilon = 4.1$ mm.
E. 25° objective prism on 4-inch lens, 7-inch focus, $H\beta$ to $H\epsilon = 2.5$ mm.
F. 25° objective prism on kinematograph lens F/1.8, 3-inch focus. $H\beta$ to $H\epsilon = 1.0$ mm.

Results from the survey are collected in two tables, one comprising nebulae which give predominantly continuous, and the other, those which give predominantly emission spectra. Nebulae whose spectra were previously known are included for the sake of completeness and are starred to indicate this fact. One nebula has thus been included which is too far south to be observed from Mount Wilson—N.G.C. 3372, the nebulosity around η Carinae. The two lists should contain all diffuse galactic nebulae for which spectrographic data are available, excepting those in the Magellanic clouds. The tables give in the first column a list number; in the second, the catalogue designation of the nebula; the third and fourth columns give galactic longitudes and latitudes; the fifth column, a rough indication of size on a scale of 1 to 5, the numbers increasing with the size; the sixth column, the instruments employed; the seventh, remarks and references.

Table I contains thirty-three objects having continuous spectra, eight of which were previously known as such. Of the latter, four give pure absorption spectra—the Pleiades, M 78, ρ Ophiuchi, and N.G.C. 7023.[1] N.G.C. 1977 and the two variable nebulae, N.G.C. 2261 and 6729, give faint bright-line images as well, and one, N.G.C. 2245, is known only through an objective prism spectrogram.

[1] Slipher reports that in the spectrum of N.G.C. 7023, "Bright $H\beta$ seems to be present but not so obviously emissive as in the star" (*Publications of the Astronomical Society of the Pacific*, **30**, 63, 1918). The involved star has bright reversed hydrogen lines. $H\beta$ does not show on a spectrogram of the nebula made by Pease.

TABLE I

DIFFUSE NEBULAE WITH CONTINUOUS SPECTRA

No.	OBJECT	GALACTIC		SIZE	INSTRUMENT	REMARKS
		Longitude	Latitude			
1.....	N.G.C. 1333	126°	−21°0	2	C	
2.....	I.C. 348	128	−17.5	2	A, B, C,	Also listed as I.C. 1985. B.D. +31°643, involved
3.....	Pleiades*	134	−22.0	5	C	See Slipher, *Lowell Bull.*, No. 55, 1912
4.....	.....	136	−15.5	2	B, C	Uncatalogued nebula, $\alpha = 4^h14^m$; $\delta = +28°2'$ (1920)
5.....	.....	141	−17.0	1	B, C	Uncatalogued nebula, $\alpha = 4^h22^m1$; $\delta = +24°32'$ (1920)
6.....	N.G.C. 1579	132	− 9.0	2	C	
7.....	I.C. 2087	141	−14.0	1	B, C	
8.....	N.G.C. 1788	171	−24.5	2	A, B, C,	
9.....	I.C. 2118	175	−26.0	5	B, D, E	Great nebulosity north preceding Rigel
10.....	N.G.C. 1977*	175	−19.0	3	B, C	Dark helium and bright hydrogen. See Slipher, *A.S.P.*, **31**, 22, 1919
11.....	2023	173	−16.5	1	A, B, C	Nebulosity around B.D. −2°1345
12.....	2068*	173	−14.0	2	B, D, E	See Slipher, *A.P.S.* **31**, 212, 1919
13.....	.....	172	−13.0	5	B, D, E	$\alpha = 5^h45^m5$; $\delta = +1°$ (1920). Brightest portion of great "spiral" in Orion
14.....	2183	181	−11.0	1	A, B	
15.....	.....	158	− 0.5	1	A, B	$\alpha = 6^h3^m1$; $\delta = +18°42'$ (1920). Comet nebula uncatalogued
16.....	I.C. 446	168	+ 0.5	1	B, C	Also listed as I.C. 2167
17.....	447	168	0.0	2	B, C	Also listed as I.C. 2169
18.....	N.G.C. 2245*	169	+ 0.5	1	B, C	See *Ap.J.*, **44**, 196, 1916
19.....	2247	169	− 1.0	1	B	
20.....	2261*	171	+ 1.5	1	A, B, C	Faint emission on strong continuous spectrum. See *Lowell Bull.*, No. 81
21.....	.....	193	− 1.5	1	B, C	Uncatalogued nebula about B.D. −12°1771
22.....	.....	312	+17.0	3	B, F	Nebulosity about π Scorpii
23.....	I.C. 4592	322	+23.0	5	B, C, F	Nebulosity about ν Scorpii
24.....	4601	323	+21.0	2	B, C	Nebulosity about B.D. −19°4359 and B.D. −19°4361
25.....	4603	319	+17.0	4	B, C, F	Nebulosity about B.D. −24°12684
26.....	4604*	320	+18.0	4	B, C, F	Nebulosity about ρ Ophiuchi. See *Lowell Bull.*, No. 75, 1916
27.....	4605	320	+16.0	2	B, C, F	Nebulosity about 22 Scorpii
28.....	N.G.C. 6726, 7	327	−17.5	2	B, C	Nebulosity about B.D. −37°13023 and B.D. −37°13024
29.....	N.G.C. 6729*	327	−17.5	1	B, C	Faint emission on strong continuous spectrum. See *Lowell Bull.*, No. 81
30.....	6914	52	− 4.5	1	B, C	
31.....	7023*	72	+14.0	1	B, C	Slipher, *A.S.P.*, **30**, 63, 1918; Pease, *A.S.P.*, **27**, 240, 1915
32.....	7129	73	+ 9.0	1	A, B, C	
33.....	I.C. 5146	62	− 6.5	2	C	

NOTES

4. Photograph by Barnard, *Astrophysical Journal*, **25**, 219, 1907. This may be I.C. 359 whose position is given as 5^m preceding and 30′ south. No nebulosity is seen in that position.

5. In one of the dark lanes in Taurus.

7. In one of the dark lanes in Taurus. See Barnard, *Astrophysical Journal*, **25**, 218, 1906.

9. Faint extensions of this nebula stretch south and west to end in a faint obscuring cloud more than 35° from the galactic plane.

11. Wolf, *Astronomische Nachrichten*, **180**, 152, 1909, describes this as gaseous emission, but his observations undoubtedly apply to I.C. 434. See note on the latter nebula following Table II.

13. This is the brightest portion of the great loop encircling the belt and sword of Orion.

15. A bright uncatalogued nebula similar to N.G.C. 2245. A thirteenth-magnitude star is at the apex of the cometary form. It is surprising to find that so bright an object has been overlooked by observers.

21. Attention was called to this uncatalogued object in *Union Observatory Circular*, No. 7, 1911.

22. See Barnard's photograph in *Astrophysical Journal*, **23**, 144, 1906.

These nebulae show a decided tendency toward clustering, and can be divided as follows:

	Number
Taurus group	1– 7
Orion	8–14
Monoceros	15–21
Scorpius	22–27
Corona Australis	28–29
Cygnus	30–33

Their distribution in the sky, although affected by this grouping, is clearly not a simple concentration along the galactic plane. In Figure 2 they are plotted in galactic co-ordinates, and it is at

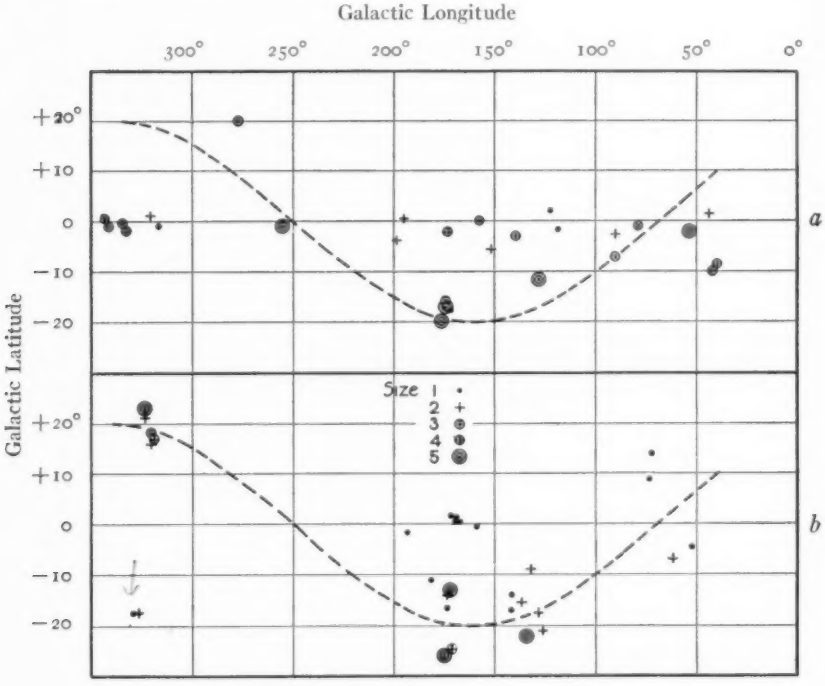


FIG. 2.—Distribution of diffuse nebulae

a. Nebulae with emission spectra

b. Nebulae with continuous spectra

once evident that most of them favor the tilted plane of bright helium stars. The Monoceros group and the isolated pair in

Corona Australis are the only exceptions. The latter, as has been mentioned, is relatively near; in fact, it is among our very nearest nebulous neighbors, and therefore can be properly assigned to the local cluster. The Monoceros group, on the other hand, may be truly galactic as judged by its position, the small size of its components, and the faintness of the stars involved.

Table II contains twenty-nine nebulae with emission spectra, thirteen of which were previously recognized as such. These objects show a greater preference for the galactic plane and less of a tendency to congregate into groups. They all lie close to the Milky Way, except the Cygnus nebula (N.G.C. 6960, 6992), N.G.C. 1499, 5128, and the Orion group. The largest objects in the galactic plane, however, fall at the nodal points of the belt of helium stars and might, from their position alone, be placed in either plane with equal reason. Starting from an assumption of double distribution, it is quite possible to divide the emission nebulae, assigning all five of the largest sizes, five out of thirteen of the graded sizes 4 and 3, and three out of eleven of the two smallest sizes, to the inclined plane. This distribution of sizes fits very well with the known fact that the local cluster of helium stars is nearer than the Milky Way clouds, and with the distribution in sizes of the "continuous" nebulae. Those assigned to the galactic plane have a very small dispersion and a mean galactic latitude of $-1°.6$, which is exactly the latitude of the galactic circle as determined by Nort.[1] So close an agreement was of course unexpected, and lends some justification to the rather arbitrary division of nebulae between the two planes.

A study of the relative intensities of the monochromatic images in Table II leads to the interesting generalization that hydrogen in the extended nebulae as represented by $H\beta$ is much stronger compared to N_1 and N_2 than is the case in the planetaries. Wilson suggested this from the intensities in two extended nebulae, N.G.C. 1976 and 3372, and established the fact that emission nebulae in the Magellanic clouds occupy a position in this respect between the normal planetaries and the extended nebulae.

[1] *Recherches Astronomiques de l'Observatoire d'Utrecht*, 7, 1917.

TABLE II

Diffuse Nebulae with Emission Spectra

No.	Object	Galactic		Size	Instrument	Remarks
		Longitude	Latitude			
1.....	N.G.C. 281	90°	− 7°0	3	B, C	One image, $N_1+N_2+H\beta$. Six hours with C much fainter than two hours' direct exposure
2.....	I.C. 59–63	90	− 2.5	2	B, C, D	Fan nebulae near γ Cass. D shows three images, $N_1+N_2+H\beta$(3), $H\gamma$(1), $H\delta$ (1)
3.....	N.G.C. 1491	118	− 1.5	1	C	Strong single image, $N_1+N_2+H\beta$
4.....	1499*	128	−11.5	5	B, C, D, E	Spectrum described in *A.S.P.*, **32,** 155, 1920. N_1+N_2 (2), $H\beta$ (2), 4686 (1), $H\gamma$ (2), $H\delta$ (1), $H\epsilon$ (1)
5.....	1624	122	+ 2.0	1	C	One image, $N_1+N_2+H\beta$
6.....	I.C. 405	139	− 3.0	3	C	Two images, $N_1+N_2+H\beta$ (2), $H\gamma$ (1). Faint continuous spectrum
7.....	N.G.C. 1952*	151	− 5.5	2	C	Four images, $N_1+N_2+H\beta$ (5), $H\gamma$ (2), $H\delta$ (0), 3727 (1). Strong continuous spectrum. See *L.O.B.*, **13**
8.....	I.C. 423	172	−17.5	1	B	Five images, N_1+N_2 (2), $H\beta$ (2), 4686 (1), 4363 (1), $H\gamma$ (2)
9.....	N.G.C. 1976*	176	−19.5	5	B, C, D, E	Orion nebula. See *L.O.B.*, **13,** and *A.S.P.*, **31,** 212, 1919
10.....	1982*	176	−19.0	2	B, C, D, E	Orion nebula. See *L.O.B.*, **13,** and *A.S.P.*, **31,** 212, 1919
11.....	I.C. 434*	174	−17.0	5	B	Bay nebula south of ζ Orionis. See Wolf, *A.N.*, **180,** 152. Five images, $H\beta$ (5), 4686 (2), $H\gamma$ (4), $H\delta$ (1), 3727 (2)
12.....	N.G.C. 2024	174	−16.0	3	B, D	N_1 (1), $H\beta$ (3), 4686 (2), $H\gamma$ (3), $H\delta$ (2), 3727 (2), faint continuous spectrum
13.....	2175	157	0.0	3	B, C	N_1 (1) $H\beta$ (3), $H\gamma$ (3)
14.....	2237	173	− 2.0	4	B, C, D	N_1+N_2 (2), $H\beta$ (1), $H\gamma$ (1)
15.....	.....	198	− 4.0	2	C	One image, N_1+N_2
16.....	2359	194	+ 0.5	2	B, C	One image, N_1+N_2. Gaseous nature predicted from direct photographs by Pease, *Mt. Wilson Contr.*, No. 132
17.....	3372*	255	− 1.0	5	.....	See *L.O.B*, **13**
18.....	5128	277	+20.0	3	C	$H\beta$ (2) 4686 (1), $H\gamma$ (2), $H\delta$ (1)
19.....	6302*	316	− 1.0	1	B	
20.....	6357	320	+ 1.0	2	C	One image, N_1+N_2
21.....	6514*	334	− 0.5	3	B, C	Trifid. See *L.O.B.*, **13,** N_1+N_2 (1), $H\beta$ (3), $H\gamma$ (2), $H\delta$ (1), 3727 (2)
22.....	6523*	333	− 0.5	4	B, C	M 8. See *L.O.B.*, **13.** N_1 (2), N_2 (1), $H\beta$ (4), 4363 (1), $H\gamma$ (3), $H\delta$ (1), $H\epsilon$ (1), $H\zeta$ (1), 3727 (2). Local variation to intensities
23.....	6611	343	+ 0.5	3	B	M 16. N_1+N_2 (1), $H\beta$ (3), $H\gamma$ (2). See *Mt. Wilson Contr.*, No. 177, p. 6
24.....	6618*	341	− 1.0	3	B	M 17. See *L.O.B.*, **13,** N_1 (4), N_2 (2), $H\beta$ (3), 4686 (0), 4361 (1), $H\gamma$ (3). Local variations
25.....	6888	43	+ 1.2	.....	B, C	$H\beta$ (2), $H\gamma$ (1), $H\delta$ (1), 3727 (2)
26.....	6960*	40	− 8.5	4	B	See Wolf, *A.N.*, **178,** 379; *ibid.*, **180,** 152
27.....	6992*	42	−10.0	4	B	See Wolf, *ibid.*, **178,** 152. Nos. 26 and 27, are really portions of one nebula—an enormous loop in Cygnus
28.....	7000*	53	− 1.0	5	B, C	Wolf, *Sitz. Heid. Akad. Wiss.*, **27,** 1, 1910
29.....	7635	79	− 1.0	3	A, B, C	$H\beta$ (5), $H\gamma$ (2), $H\delta$ (1), 3727 (4)

NOTES

Campbell and Moore were unable to see bright lines in N.G.C. 2024, 6992, and 7000. N.G.C. 6523, 6618, and 7635 each has at least one image of wave-length shorter than 3727.

7. The continuous spectrum in N.G.C. 1952 is so strong that the nebula might equally well be included in Table I.

11. I.C. 434. This is the remarkable Bay nebula stretching south from ζ Orionis, whose sharp edge on the following side is indented by a dark cloud billowing out from the obscured region bordering on the bright nebula. My plates give an emission spectrum which agrees with that described by Wolf in *Astro-*

nomische Nachrichten, **180**, 152, 1908, and ascribed by him to N.G.C. 2023. N.G.C. 2023, however, is a typical nebulous star, B.D. −2°1345, in the obscured region following I.C. 434. The nebulosity around it has a strong continuous or rather an absorption spectrum with no trace of emission. Furthermore, Wolf's remarks "sudlich von ζ Orionis—umittelbar nordlich von die grossen Bucht . . . ." clearly apply to I.C. 434. In view of these facts, I assume the nebula whose spectrum Wolf describes in *Astronomische Nachrichten*, **180**, 152, is really I.C. 434 and so list that nebula as one whose spectrum was previously known. N.G.C. 2023 is listed among those giving continuous spectra which were not previously known.

13. Continuous spectrum fairly strong. Emission spectrum checked by a slit spectrogram.

15. This is an uncatalogued nebula described by Knox Shaw in *Helwan Bulletin*, No. 15. Discovery announced in *Union Observatory Circular*, No. 7, 1911.

28. N.G.C. 7635, formerly known as a nebulous star, appears to be a large planetary immersed in diffuse nebulosity. The brightest portions of the non-planetary nebulosity give the emission spectrum described.

The normal ratio N_1, N_2, and $H\beta$ in the planetaries is 10:3:1. From the observations of Campbell and Moore and of Wilson, data can be gathered for extended nebulae as follows:[1]

	N_1	N_2	$H\beta$
N.G.C. 1976	10	3	5
3372	10	3	5
6514	3	1	10
6523	3	1	10
6618	10	3	5

Table II furnishes data of inferior accuracy, but strongly supporting those listed above.

	N_1+N_2	$H\beta$
N.G.C. 1499	1	2
I.C. 423	1	1
I.C. 434	0	5
N.G.C. 2024	1	3
2175	1	3
2237	2	1
5128	0	2
6611	1	3
6888	0	2
6960, 6992	0	2
7000	0	2
7635	0	5

N.G.C. 1977 and 1982 are connected with N.G.C. 1976, the Orion nebula, and these, together with the outer region of the Orion nebula itself, show a decided weakening of the N_1 and N_2

[1] *Publications of the Lick Observatory*, 13.

lines, as compared to the 10:3:5 relation for the trapezium region. A spectrogram made at Mount Wilson with the slit east-west, just south of the B8 star B.D. $-5°1305$, $12'$ south and preceding the trapezium, shows Hβ ten times as strong as N_1 and apparently just stronger than λ 3727.[1] It is interesting to note that the nebulosity condensing about the star shows a pronounced strengthening of the continuous spectrum without affecting the emission lines.

N.G.C. 281, 1491, 1624, 2359, 6357, and I.C. 59, 63, and 405 show such faint overlapping images that they cannot be separated into components for the estimation of relative intensities.

In no case, excepting N.G.C. 1952, is Hβ less than half the intensity of N_1. In this exceptional case, as studied from a slit spectrogram by Sanford, the local variations and overlap of double lines interfere with estimation of relative intensities and the only statement which can be made is that Hβ and N_2 are of about the same order of intensity.

The significance of this generalization is not clear as yet. Of the six giant planetaries[2] only one, N.G.C. 7635, shows the stronger Hβ, and the same ratio holds for small planetaries out of the Magellanic clouds discussed by Campbell and Moore. The most striking examples of these latter, N.G.C. 40, I.C. 418, N.G.C. 4361, and B.D. $+30°3639$, are in no way exceptional in appearance or in their nuclear spectra. The nuclei, however, are unusually bright as compared with the general average.

Among the non-galactic nebulae showing emission lines, two described by Campbell, N.G.C. 1068 and 4151, seem to have the normal planetary ratio, 10:3:1 for N_1, N_2, and Hβ, while three others described by Pease and by Slipher, M 33, N.G.C. 4214 and 4449 show the relatively stronger Hβ.

Tables I and II more than double the number of known emission spectra, and quadruple that of known continuous spectra. The latter now outnumber the former for separately catalogued objects; but in view of the greater tendency to group among the nebulae

[1] "Apparently" in that an ordinary lens and a Seed 30 plate were used. Quartz or U.-V. glass and Seed 23 plates would show λ 3727 as much stronger than Hβ.

[2] The term "giant planetary" is used to describe those with diameter greater than $2'$. There are six such planetaries.

with continuous spectra, it is preferable to regard the numbers as about equal. As emission nebulae are much more easily identified for a given surface-brightness because of the discontinuous distribution of light in their spectra, it seems a reasonable extrapolation to assume that continuous spectra are actually more numerous than emission among the diffuse galactic nebulae.

A study of direct photographs fails to give any necessary and sufficient criteria certain for predicting by inspection the nature of the spectrum of a given diffuse nebula. There are several general indications, but each has its exceptions. Filamentary and wispy nebulosity usually has an emission spectrum, as, for example, N.G.C. 1499, 1952, 1976, 2359, 6960, and 6992. This is not a necessary condition and is approximately satisfied in the "continuous" nebulosity about the Pleiades and 22 Scorpii; moreover N.G.C. 1952, the Crab nebula, has so strong a continuous background for its bright-line images that its spectrum could be classed as continuous almost as reasonably as emission. On the other hand, a smooth, cloudy structure is usually confined to "continuous" nebulosity, as in that about ν Scorpii and ρ Ophiuchi, but this again is approximated in the emission nebulae N.G.C. 2024 and the Trifid.

Nebulae with "continuous" spectra are usually associated with greater obscuration than are emission nebulae, although striking exceptions are found in Orion and N.G.C. 7000. It is of course a natural supposition that such vast bodies must be at least partly opaque, and that the "continuous" would be more so than the emission nebulae. Observation shows this to be the case. Obscuration is in fact a universal characteristic of diffuse galactic nebulae wherever the angular areas are large enough to warrant conclusions. The best direct evidence that I have found for transparency in any degree is presented by the helical nebula in Aquarius, N.G.C. 7293, the largest recognized planetary. Photographs made with the 100-inch reflector show three or four small non-galactic nebulae, including one spindle, within the luminous area of the planetary. The great size and galactic latitude of N.G.C. 7293 render it highly probable that the planetary is relatively near, at least nearer than the small nebulae, which, therefore, must be considered as shining through the planetary.

The brightest nebulae have emission spectra; the largest, continuous spectra. In general, however, the two classes mix pretty thoroughly when arranged in order either of size or of brightness. "Continuous" nebulae show a greater tendency to condense around stars, although most of the galactic nebulae have stars involved, and perhaps all have stars associated with them.

SPECTRAL TYPES OF STARS INVOLVED IN DIFFUSE NEBULOSITY

A study of the spectral types of such stars shows that those involved in "continuous" nebulae are of later types than those involved in emission nebulae. This conclusion is based on examination of slit spectrograms made with Cassegrain spectrographs on the 60-inch and 100-inch reflectors. One prism and an 18-inch camera were generally used, although for some of the faintest stars a 7-inch camera was necessary. Table III gives the types of stars involved in 29 of the "continuous" nebulae, which are designated by the list numbers of Table I.

Three cases are exceptional—the faint K8 star in No. 4, around which the nebulosity condenses so strongly and symmetrically that the star must be regarded as involved, and the nuclei of the two variable nebulae N.G.C. 2261 and 6729. V. M. Slipher reports the nuclear spectrum of N.G.C. 2261 as consisting of bright and dark lines agreeing closely with Nova Aurigae in its later stages. He suspected that the nucleus of N.G.C. 6729, R Coronae Australis, was similar, but three spectrograms made with the 100-inch reflector (7-inch camera) show a peculiar G-type spectrum with bright reversed hydrogen and enhanced iron lines. When these three cases are disregarded, the mean type of the other stars is about B4. None is earlier than B1.

There is a decided tendency toward uniformity of stellar type within the various groups. The Taurus group contains nothing earlier than B5. The Orion group is B2 and B3, with one exceptional B1 star in N.G.C. 1977, a nebula giving bright lines as well as a strong continuous spectrum. The stars in the Monoceros nebulae are B1 and B2, and those of the Scorpius group are B2 and B3 as in Orion, excepting the isolated case of I.C. 4601,

TABLE III

STARS INVOLVED IN NEBULAE WITH CONTINUOUS SPECTRA

No.	Nebula	Pv. Mag. of Stars	Spectrum of Stars	
1	N.G.C. 1333	10.6	B8	
2	I.C. 348	8.4	B6	B.D. +31°643
		9.8–11.6	B8–A2	9 stars
3	Pleiades	.....	B5	Maia and Merope
4	.....	12.5	K8	Probably a dwarf
6	N.G.C. 1579	12.0–12.2	A0–B5	2 stars
8	1788	10.0–13.0	B8–B8	2 stars
10	1977	4.6	B1	Boss 1364
11	2023	7.8	B2	B.D. −2°1345
12	2068	10.4–10.8	B5–B8	B.D. +0°1177
14	2183	14.0	B3	
15	.....	13.5	B1	
16	I.C. 446	11.3	B1	
17	447	8.1	B1	B.D. +10°1159
18	N.G.C. 2245	10.7	B1	Bright Hβ suspected
19	2247	8.8	B2p	Bright Hβ and Hγ
20	2261	Var.	Pec.	Approximates a nova spectrum
21	.....	8.2	B1	B.D. −12°1771
22	.....	3.1	B2	π Scorpii
23	I.C. 5592	4.2	B2	ν Scorpii
24	4601	7.1–8.4	B8–A0	4 stars
25	4603	7.8	B2	B.D. −24°12684
26	4604	5.2–5.9	B2–B3	2 components of ρ Ophiuchi
27	4605	4.9	B3	22 Scorpii
28	N.G.C. 6726, 7	7.2–9.4	B9–B9	2 stars
29	6729	Var.	Gp	R Coronae Australis. Resembles T Tauri
30	6914	9.3–9.9	B5–B5	B.D. +41°3731 and B.D. +41°3737
31	7023	7.2	B2p	Bright Hβ and Hγ
32	7129	10.2–12.4	B3–B8	3 stars
33	I.C. 5146	10.0	B1	B.D. +46°3474

NOTES

4. Nebulous star north following Barnard's nebula.

15. Nucleus of cometary nebula resembling N.G.C. 2245. It is not catalogued.

17. There is a group of six stars in this nebula, some of which are certainly not involved.

24. Boss 4150, visual mag. 6.2, G5 giant, is involved in nebulosity connected with No. 24.

28. B.D. −37°13017 and 13018, visual mag. 6.5 and 6.7, B5 and B6, are involved in connecting nebulosity.

29. R Coronae Australis has bright unsymmetrically reversed hydrogen and enhanced iron lines on an absorption spectrum that is approximately a G-type but which has contradictory characteristics. The spectrum resembles that of T Tauri except that it has no bright H and K.

in which are involved four stars, B8 to A0. The Corona Australis group really comprises two double stars in addition to R. The types are B5, B6, B8, and B9, R itself being, as mentioned above, a peculiar later type.

The Monoceros group comprises all the "continuous" nebulae which can be assigned to the galactic plane with any degree of certainty. This distinction is emphasized by the fact that they contain, as a group, the earliest types of involved stars. The only other B1 star (excepting the transitional case of N.G.C. 1977 mentioned above) is central in I.C. 5146, the Cave nebula in Cygnus. This object is so near a nodal point of the inclined plane that it can be placed in either belt with equal justification. These facts raise a question as to whether or not there may be a real difference in type between stars involved in nebulae belonging to the galactic plane as compared with those belonging to the local cluster. The various groups differ so much among themselves, however, that no great weight can be assigned to results from one of their number. Moreover, there seem to be some later-type stars in the cluster around S Monocerotis and possibly in I.C. 447.

The K8 star in No. 4 is not unique. Heretofore it has been thought that all stars involved in nebulosity are B-type or earlier. The following list, which does not include several known cases of A stars, some of which are of the α Cygni type, shows that this is not rigorously true.

1. B.D. $+31°597$	K2 giant
2. B.D. $+28°645$	F8±
3. T Tauri	G peculiar with bright lines
4. No. 4	K8 dwarf
5. Boss 4150	G5 giant
6. R Corona Australis	G peculiar with bright lines

These six objects have all been photographed directly with the 100-inch reflector and, in each case, the nebulosity condenses about the star so obviously that there can be little doubt that the stars are really involved. Some may be cases of stars and nebulosity meeting in the course of the peculiar motions through space, but others, notably T Tauri and R Coronae Australis, must surely be

inherently associated with the nebulosity surrounding them. None of them, however, shows any indications of nebulosity condensing into stars.

Absorption spectra of diffuse nebulae are reported by Slipher and by Pease as agreeing with the spectra of the brightest involved stars, as well as could be determined with the small dispersions employed. In this connection it is of interest to mention the following nebulae with predominantly continuous or absorption spectra which have bright-line stars involved.

Nebula	Star
Pleiades	Bright Hα in several of the brighter stars
N.G.C. 2247	Bright line B1p
N.G.C. 7023	Bright line B2p
N.G.C. 2261	Approximately a Nova spectrum[1]
N.G.C. 6729	G peculiar with bright hydrogen and enhanced iron lines

The spectrum of the Pleiades nebulosity has not yet been examined in the Hα region. No slit spectrogram has been obtained of N.G.C. 2247, and the objective-prism spectra could easily obliterate faint emission images. N.G.C. 7023 and 6729 are suspected, N.G.C. 2261 is definitely proved by Slipher, to have spectra corresponding in detail to the spectra of the stars involved. There is thus no evidence against, and some in favor of, the assumption that nebular spectra that are predominantly "continuous" are the spectra of reflected starlight.

Table IV indicates types of stars involved in nebulae with emission spectra. N.G.C. 3372, the η Carinae nebulosity, is not included because its position is such that no investigation could be made here concerning the question as to which stars are involved and which are not. η Carinae itself is usually accepted as being so involved, and if this is true, it is the one example known of a peculiar bright-line star in emission nebulosity. The Draper *Catalogue* lists two Wolf-Rayet stars within the limits of N.G.C. 3372, but there again the question of their being involved, or simply aligned, requires special investigation that cannot be carried out at Mount Wilson.

[1] *Lowell Observatory Bulletin*, No. 81, 1918.

There are two probable cases of Wolf-Rayet stars associated with diffuse nebulae having emission spectra. These are N.G.C. 2359

TABLE IV

STARS INVOLVED IN NEBULAE WITH EMISSION SPECTRA

No.	Nebula	Pv. Mag. of Stars	Spectrum of Stars	
1.....	N.G.C. 281	8.6–10.2	Oe5	4 components of B.D. +55°191
		10.3–11.6	Bo	3 stars
3.....	1491	10.6	Bo	
5.....	1624	13.0–14.0	Oe5	3 stars. Magnitudes estimated
6.....	I.C. 405	5.8	Bop	Boss 1249
9.....	N.G.C. 1976	5.4–7.9	Oe5–Bo	4 components of Trapesium
10.....	1982	6.8	B1p	Bond 734. 4686 strong for type
13.....	2175	7.5	Oe5	B.D. +20°1284
14.....	2237	7.4–8.2	Oe5	4 brightest stars of the cluster
16.....	2359	11.0	Od	Magnitude estimated
21.....	6514	7.8–8.5	Oe5–Bo	2 components of B.D. −23°338
22.....	6523	6.1–6.9	Oe5–Bo	2 brightest stars in M 8. B.D. −23°13814–16
23.....	6611	8.3–9.2	Oe5–Bo	3 brightest stars in M 16.

NOTE

21. B.D. −22°4510, pv. magnitude 7.25, A3p (α Cygni type) is central in the northern lobe of the trifid nebula, N.G.C. 6514. The excessive color-index of this star, +0.80 magnitudes, together with the pronounced general absorption of the nebulosity, suggests that the star is actually within the nebula.

and 6888. Photographs of both nebulae have been published by Pease.[1] N.G.C. 2359 shows a ring and tangential streak suggesting the present form of the nebula surrounding Nova Persei No. 2. An eleventh-magnitude Ob star is approximately central in the ring and hence presumably associated with the nebula. N.G.C. 6888 is a segment of an ellipse with the Ob star B.D. +37°3821 of magnitude 7.1 near the center of the ellipse. The photograph suggests a ring of nebulosity of non-uniform brightness, inclined to the line of sight. Both nebulae have some resemblance to the planetaries or to a transitional type between planetary and extended forms. Both the nebular forms and types of stellar spectra suggest the possibility that these two nebulae are remnants of former outbursts of novae.

γ Cassiopeiae is probably associated with the emission nebulae I.C. 59 and 63. The star is clearly not involved, but the fan-

[1] *Mt. Wilson Contr.*, No. 186; *Astrophysical Journal*, **51**, 276, 1920.

shaped masses of nebulosity pointing toward that star suggest an intimate association. If this is true, γ Cassiopeiae is the one known case of a bright-line B-star associated with emission nebulosity. The type is called Bo peculiar.[1] ζ Orionis can with equal justification be considered as associated with N.G.C. 2024. In fact, all the belt stars of Orion might be thought of as associated with emission nebulosity, for the faint cloud in which they are immersed brightens in the portion known as I.C. 434, the bay nebula south of ζ Orionis, sufficiently to permit its spectrum to be identified as emission. These stars are of the Bo type.

Another feature of the table is the marked tendency of Oe5 stars to form clusters in emission nebulae. Examples are N.G.C. 281, 1624, 2237, and 6611. Definite data are restricted to the brighter members of these clusters, but small dispersion spectrograms suggest that the fainter members are of somewhat later types and that the brighter ones alone determine the spectrum of the nebulosity.

N.G.C. 6618 (M 17) has no stars obviously involved, but there are indications of a cluster on its southern border. Two of the brightest of these are B8 and two fainter ones are Bo. General indications from focal-plane slitless spectrograms are that the two stars mentioned are the only late B-type stars in the group. A reasonable conclusion is that the two B8 stars are merely aligned, and that the group of fainter stars, if they are connected with the nebula, are of the usual type—Bo. The B8 stars are B.D. $-16°4827$ and $-16°4828$.

The main features of Table IV are the close limitation of the stars within the types Oe5 and Bo—at least for the brighter stars in each nebula—and the relatively rare occurrence of bright lines. These are four probable cases of emission nebulae associated with bright-line stars, but in no case do the spectra of star and nebula agree. The fact is well established that in the case of emission nebulae, the nebular spectrum and the spectra of stars involved or associated do not agree. This recalls Wright's remarks on the

[1] B.D. $-10°1848$ may be another case, but the spectrum of the nebulosity is so confused on my plates that the statement cannot be made definitely. The star is Bop with bright hydrogen lines.

rare agreement between nebular and nuclear spectra among the planetaries.

The progression in stellar type from gaseous to "continuous" nebulae seems to be definitely established. There is no overlap save in N.G.C. 1982, which shows marked transitional characteristics in its spectrum. The sequence is well illustrated in the Orion nebulae of which the spectra have been investigated by Slipher and by Campbell and Moore.

N.G.C. 1976 gives a typical nebular emission line and a weak continuous spectrum. The trapezium stars are of type Oe5 and Bo.[1]

N.G.C. 1982 gives a transitional spectrum. It is predominantly emission, but has a very considerable continuous background which intensifies in a marked degree about the involved star Bond 734. This is a B1 star, with λ 4686 unusually strong for the type. It might be called an early B1.

N.G.C. 1977. The spectrum is predominantly continuous with bright hydrogen and dark helium lines. No nebulium can be seen. The involved star, Boss 1364, is of type B1.

N.G.C. 2023. The spectrum is continuous with dark hydrogen and helium lines, and that of the involved star, B.D. $-2°1345$, is B2.

N.G.C. 2068 (M 78). The spectrum is continuous with dark hydrogen and helium lines and was classed by Slipher as probably late B. The stars involved are classed as B3 and B5, but subject to a rather large uncertainty. My own plates tend to place the nebular spectrum as not later than B5.

N.G.C. 2237 in Monoceros might be placed at the head of this sequence as it gives a pure emission spectrum with no continuous background perceptible. The four brightest stars involved, which have been investigated, all show fine Oe5 spectra.

SPECTRA OF PLANETARY NUCLEI

The progression is so pronounced that it seemed advisable to investigate the possibility of extending it into the other type of galactic nebulae, the planetaries. Wright has shown that some

[1] It has been previously mentioned that "continuous" nebulosity condenses strongly about the B8 star B.D. $-5°1305$ in the outer region of N.G.C. 1976, while the emission lines of the nebula are not affected by the star.

planetary nuclei have bright lines or bands, and that others do not. Where emission does occur it is probably of the Wolf-Rayet type. He has not published results for any of the nuclei of giant planetaries, and, as these seem to have the closest affinity to extended nebulae, their spectra have been observed at Mount Wilson.

As an arbitrary division, those planetaries whose mean diameter exceeds two minutes of arc are called giants. There are six such, all within reach in this latitude.

N.G.C. 246	N.G.C. 6853 (Dumbbell)
1514	7293 (Helix)
3587 (Owl)	7635

Two of them have central stars bright enough for the Cassegrain spectrograph with one prism and an 18-inch camera on the 100-inch reflector. These are N.G.C. 1514 and 7635, whose central stars are, respectively, B.D. $+30°623$, 9.4 photo-visual magnitude, and B.D. $+60°2522$, 8.7 photo-visual magnitude. Their spectra are similar and of a type not covered by the Harvard classification. They show no bright lines or bands. The following dark lines are present.

$H\beta$	$H\delta$	4200[1]	4686 faint and hazy
$H\gamma$	4542[1]	4026[1]	4471 just perceptible

To these may be added λ 4481 in B.D. $+30°623$ nearly as strong as λ 4542, and in B.D. $+60°2522$, λ 4147 stronger than λ 4471, and H and K faint and sharp. With these exceptions, the spectra could be described as Od with the bright lines suppressed to the extent of a trace of absorption in λ 4686. Their position is intermediate between the Wolf-Rayet type and Oe5. Radial velocities for four plates of each are $+35.4$ km for B.D. $+30°623$ and -34.5 km for B.D. $+60°2522$.

A single slit spectrogram of the central star in N.G.C. 246 made with one prism and a 7-inch camera shows a spectrum similar to B.D. $+60°2522$, the central star in N.G.C. 7635. In all three objects, the line λ 4542 is the strongest except the hydrogen lines.

By way of comparison, a spectrogram of the nucleus of the smaller planetary I.C. 2149 was obtained, using one prism and

[1] The lines $\lambda\lambda$ 4542, 4200, and 4026 are those discovered by E. C. Pickering in the spectrum of ζ Puppis, for which he employed the designation $H\gamma'$, $H\delta'$, and $H\epsilon'$, respectively.

an 18-inch camera on the 100-inch reflector. This nucleus is one for which Wright reported a continuous spectrum with no bright lines. An exposure of eight hours gave a legible spectrum in spite of very poor seeing conditions. The rather faint continuous spectrum of the nucleus holds up unusually well toward the violet, and is crossed by the bright lines of the nebula, so sharp and narrow that their source is unmistakable. Only three dark lines can be detected. Hβ and Hγ are very faint and hazy and almost obliterated by the strong bright nebular lines superposed. The third dark line is λ 4542, exceedingly faint, but free from any nebular line. No trace of λ 4686, either bright or dark, can be seen. Thus the nuclear spectrum, freed from the bright lines due to the nebula, is rather similar to a weak spectrum of the three central stars discussed above.

Slitless spectra have been obtained for the nuclei of all six of the nebulae. The dispersion is small, about 5.0 mm from Hβ to Hϵ, and conclusions based on them are not as certain as one would wish. All six are essentially similar; at least no difference could be made out on the small-dispersion plates. No bright lines or bands are seen, and all show the well-known strength in the ultraviolet which Wright first reported. This similarity of slitless spectrograms, together with the results of a detailed study of three higher-dispersion spectra taken with a slit, permits the assumption that we have in these central stars a class of objects intermediate between stars involved in extended emission nebulae and in the smaller planetaries.

Wright himself published observations of only two planetaries with mean diameters greater than one minute of arc. These are N.G.C. 4361 and 6720. In both cases the nucleus gave a continuous spectrum with no bright lines. His fifteen nebulae whose nuclei show no bright lines have a mean diameter of about 30″ as against 20″ for the fifteen whose nuclei do show bright lines, probably of the Wolf-Rayet type.[1]

The evidence, as far as it goes, points to a progression in spectral type of central or involved stars from the small planetaries to the large ones, and this progression joins immediately on to that of the

[1] *Publications of the Lick Observatory*, **13**, 252, 1918.

extended nebulae. The complete sequence of stars involved in galactic nebulae can be represented as follows:

Small planetaries	Wolf-Rayet
Large planetaries	Intermediate between Wolf-Rayet and Oe5
Extended emission nebulae	Oe5 and Bo
Extended "continuous" nebulae	B1 and later

The overlap is surprisingly small and for the most part confined to nebulae with unusual forms or spectra. No conclusions have been formed as to the end of the sequence, although it may be significant that the stars of latest type seem to favor faint nebulosity and pronounced obscuration. N.G.C. 2359 and 6888, on the assumption that the Ob stars are truly associated, fall out of place. In both cases, however, there is evidence of a ring structure that suggests a nova origin or at least an affinity with the planetary type.

ASSOCIATION OF GALACTIC NEBULOSITY WITH STARS

This intimate relation between spectral type of nebula and of involved stars raises a presumption that one is a consequence of the other. It seems more reasonable to place the active agency in the relatively dense and exceedingly hot stars than in the nebulosity, and this leads to the suggestion that nebulosity is made luminous by radiation of some sort from stars in certain physical states. The necessary conditions are confined to certain ranges in stellar spectral type and hence are possibly phenomena of effective temperature. The nebulous material itself must be in a physical state sensitive to the stellar radiation, and close enough for the density of radiation to be effective. The abrupt transition from emission to "continuous" nebulosity between stellar types Bo and B1 suggests a critical point in the spectral sequence or possibly effective temperature below which stellar radiation is incapable of exciting nebulous material to emission luminosity. From thence down the spectral sequence the luminosity gives a continuous spectrum and probably partakes more and more of the nature of reflected light.

A theory of nebular luminosity built on these lines meets a first obstacle in the necessity for locating stars conspicuously associated with each galactic nebula, of the required spectral

type, and properly placed to energize the nebulosity. Planetaries offer no great difficulty. There is doubt in some cases as to whether the nuclei are truly stellar, but there is usually a condensed center which may well conceal a star or take the place of a star as a center of radiation. In several extended nebulae, however, there is a conspicuous absence of any obviously dominating star or group of stars. Such of those as give continuous spectra show pronounced obscuration in and surrounding the nebulosity, and offer the possibility that stars capable of playing the required rôle are present but entirely or partially obscured. Nos. 4, 5, 6, and 7 in Table I are examples.

Emission nebulosity exhibits much less general absorption, possibly because the matter is in a more highly dissociated state. Here the assumption of obscuration generally fails, and the radiation centers must be sought among the multitude of stars always found within, or near to, the nebulosity. Such stars need not be apparently bright, for the apparent surface luminosity of nebulae is independent of the distance. Furthermore, several of the giant planetaries, for instance, N.G.C. 3587, 6853, and 7293, have bright nebulosity with central stars of the thirteenth to the fourteenth magnitude. Such objects then as N.G.C. 1499 and the nebula in Cygnus, N.G.C. 6960 and 6992, might, with no great stretch of the imagination, be considered as receiving affective radiation from some of the neighboring stars, after the manner in which N.G.C. 2024 probably receives its energy from ζ Orionis.

These suggestions may be applied to the nebulae considered in this paper. Table I contains only six nebulae with continuous spectra, which have no stars obviously involved or conspicuous on direct photographs for location and brightness. They are Nos. 4, 5, 6, 7, 9, and 13. The first four fall in the Taurus group and lie in regions of complete obscuration. Involved stars would need to lie on the near side or very close to the nearer surface of the nebulae in order to be seen at all. In two of these four cases, Nos. 4 and 6, faint stars are present which are almost certainly dimmed by intervening nebulosity. It is possible and even reasonable to assume that bright stars may be involved or associated with all four of these objects, but partially or completely hidden by the obscuring clouds.

No. 9 is the nebulosity north of and preceding Rigel. The form of the nebula approximates an arc with Rigel at the center. Moreover, several fan-shaped details are present which in each case point toward that star. In short, the nebula shows a considerable degree of radial symmetry with Rigel as the point of convergence. The spectral type of Rigel, B8p, and the absolute magnitude, -5.5 according to Kapteyn, are significant. The nebulosity extends to a distance of $2°.5$ from the star which, in terms of actual distance across the line of sight, is of the order of twenty light-years at the distance of Rigel. This seems an enormous distance over which to assume stellar radiation to be effective in illuminating nebulosity, but a comparison with the better-known Pleiades nebulosity indicates that the two cases are comparable, and Hertzsprung's[1] discussion of the Merope nebula lends considerable weight to the suggestion that reflected starlight can account for the whole of the nebular luminosity in that particular case. In terms of absolute magnitudes Rigel is about 4.7 magnitudes brighter than Merope and hence will have the same illuminating power at 8.7 times the actual distance of similar nebulosity from Merope; or since Rigel is about 1.5 times as distant as Merope from the earth, to an angular distance of about 5.8 times as seen from the earth. Nebulosity comparable in brightness to the nebulosity near Rigel exists nearer to Merope than to any other of the bright stars of the Pleiades, and it extends to a distance considerably more than $1/5.8$ times its angular distance.

Inclusion of all the Pleiades stars will not entirely destroy the analogy. According to Trumpler's list of cluster stars, the equivalent brightness of the Pleiades cluster is of the order of magnitude 1.3 or about -3.7 absolute, and the center of the cluster is about $6'$ west of Alcyone. Rigel then is 1.8 magnitudes brighter than the entire cluster and would have equal illuminating powers on nebulosity at about 1.4 times the angular distance of equivalent nebulosity from the center of the cluster. The equivalent distance in the Pleiades cluster is about $100.'$ The actual nebulosity is rather sharply divided into bright inner clouds involving the more luminous stars and extending in parts to about $50'$ from the center, and

[1] *Astronomische Nachrichten*, **195**, 449 (No. 4679), 1913.

very faint exterior clouds extending to 3° or 3°.5 from the center. The position of the nebulosity near Rigel would seem to fall between these extremes. This discussion disregards inclinations to the line of sight of the direction from star to nebulosity, and hence leaves an element of uncertainty in the conclusion. It does seem plausible, however, to regard the relation of Rigel to its neighboring nebulosity in the same category as the relation between stars and nebulosities in the Pleiades cluster.

No. 13, the great loop, sometimes called the spiral, around the belt and sword of Orion, offers difficulties of another sort. The belt stars and the general aggregation of fainter stars in the vicinity are sufficiently bright to account for the nebular luminosity on the same basis as in the case of Rigel and the Pleiades, but the continuous spectrum of the nebulosity does not fit the Bo spectral types of the brighter belt stars. These same stars appear to produce an emission type of illumination in nebulosity immediately adjacent to them, N.G.C. 2024, I.C. 434, etc.; yet if they truly do illuminate the more distant loop, it is with a different light altogether. It may be that the physical state of the loop nebulosity is different from that in the closer objects—that the physical state of all nebulosity depends upon distance from, and spectral type of, associated stars. Or, again, the ability of stellar radiation to produce emission luminosity may be restricted to certain limits of distance which in this case are exceeded.[1]

The facts seem definite—the nebulosity close to the belt stars gives emission spectra while that far away gives a continuous spectrum. Several nebulae giving continuous spectra, as, for example, N.G.C. 2023, are nearer to the belt than is the loop, but they lie on the near side of an obscuring cloud which seems to veil them from the influence of the belt stars and permits them to shine by the undisturbed action of their own involved stars. Slipher suggested that spectra of the Orion nebulosities change from emission to continuous or rather to absorption, as one proceeds outward from a center—probably the great nebula around

[1] The brightest portion of the loop is nearest the belt stars. The distance across the line of sight to the nearest belt star—ζ Orionis—is about forty light-years.

θ Orionis, and these new observations may be but another application of some law. However this may be, the loop in Orion, if it does receive its light from the group of stars that includes the belt, is the one known example of a nebula giving a predominantly continuous spectrum, having as the brightest stars associated with it those of a type earlier than B1.

The result of this examination is as follows: twenty-six out of thirty-three nebulae giving predominantly continuous spectra have prominent stars obviously involved in the nebulosity; in six of the remaining cases more or less plausible means can immediately be suggested to account for the absence of dominating stars within the nebulae; and in the last case, exceptional in many respects, there exists at least possible means of accounting for the nebular illumination as originating in stars.

The case of the emission nebulae is nearly as strong. Among those listed in Table II the following do not have early type stars actually within their borders:

Nos. 2, 4, 7, 8, 11, 12, 25 (26 and 27), 28.

No. 2, I.C. 59, 63—the fan-shaped nebulae near γ Cassiopeiae. That star is obviously associated with, although not involved in, the nebula. The very form of the nebulosity seems determined by radiation or repulsive action from the star which lies at a center of radial symmetry with respect to the fans. The spectral type of γ Cassiopeiae, Bop with bright lines, conforms to the rule previously established concerning the relation between stellar and nebular spectra.

No. 4, N.G.C. 1499—ξ Persei is the brightest neighboring star. The nebula lies on a rough arc, concave to ξ Persei, which can readily be considered as occupying the center of the arc. The star is of type Oe5 and hence conformable to the nebular spectrum. No other star in the vicinity brighter than ninth magnitude has a spectrum earlier than B3.

No. 25, N.G.C. 6888—a long segment of an ellipse, of which B.D. $+37^{\circ}3821$ occupies the center. The stellar type is Ob, hence the star and nebula seem to resemble N.G.C. 2359. No other star in the neighborhood has a spectrum earlier than B5. The only brighter star near is of K-type.

These three cases offer positive evidence of association of star and nebulosity. In each, one definite external star appears to dominate the nebula, its position approximating a center of radial symmetry, its spectral type conforming to the established rule. No rival claimants can be found for any of the positions.

No. 12, N.G.C. 2024—ζ Orionis, Bo, a sort of super-giant with an absolute magnitude of -4.17 according to Kapteyn, is conveniently located to energize the nebula. Direct photographs give an instant impression that this star illuminates the nebula, although the details of nebulosity do not show such marked radial structure as is found in the three cases cited above.

No. 11, I.C. 434—the Bay nebula south of ζ Orionis. This seems part of a cloud involving the belt stars and σ Orionis. In this particular portion, both ζ and σ can be considered as sources of illumination, both from position and from spectral type.

No. 8, I.C. 423—a small loop between δ and ϵ Orionis, nearer the former. Both these stars from their spectral types can be considered as the energizing agents. Their positions bear no obvious relation to the figure of the nebula, but their distances are within reason unless greatly distorted by projection.

These three cases do not offer such definite evidence as the first three discussed. They pass from positive in No. 12 to suggestive in No. 8.

The last three cases, Nos. 7, 28, and 26 and 27, offer more serious difficulties. One indeed, 26 and 27, seems flatly to defy explanation on any observational basis.

No. 7, N.G.C. 1952, the Crab nebula, has two faint stars about centrally located. The brighter is of about 15.5 photographic magnitude and the other only slightly fainter. The nebular spectrum is strongly continuous with widely doubled bright lines. Curtis includes the nebula among the planetaries, although he calls it a doubtful classification. Exposure-ratio plates made at Mount Wilson indicate a decided negative color-index for the brighter star at least, and this, together with their approximately central position, permits the assumption that one or both are involved in or associated with the nebula. There are no bright

stars in the neighborhood which can be considered as sources of energy, either from position or spectral type.

The question, then, is whether or not the faint central star or stars can dominate the nebula. The best answer is another analogy, this time with the Helical nebula in Aquarius, the giant planetary, N.G.C. 7293. This nebula has a diameter about three times that of the Crab and a central star about two magnitudes brighter. The relation between stellar magnitude and square of the radius are of the same order. If the Crab were at three times the distance of the Helical nebula the two objects would be comparable in size and brightness of their central stars. If the planetaries are energized by their central stars, then one may assume as a possibility that the same is true of the Crab nebula.

No. 28, N.G.C. 7000—the North America nebula. This object gives a considerable continuous spectrum with faint emission. Several stars from sixth to ninth apparent magnitude are involved, and heavy obscuration is evident around the borders, especially in the southern portion. The nebulosity is cloudy and devoid of filamentous detail. In a general way it recalls the appearance of the Trifid. The spectrum also has some resemblance to that of the Trifid, although this latter nebula has a stronger emission and a weaker continuous background. The stars involved in N.G.C. 7000 are all later than B1, and hence can account for only the continuous portion of the nebular spectrum.

Inspection of small-scale photographs of this nebula, for instance, those made by Barnard with the 6-inch Willard lens, suggests that α Cygni may be associated. The Trifid nebula offers a possible analogy, for in the north lobe of that object is a star of the same enhanced A-type as α Cygni. The star is B.D. $-22^{\circ}4510$, photo-visual magnitude 7.2, with a spectrum remarkably similar to that of α Cygni. The star has a color-index of about 0.8 magnitude and hence is regarded as involved in the nebulosity. The Trifid nebula gives an emission spectrum on a continuous background. The emission portion can be attributed to the Oe5 star B.D. $-23^{\circ}338$ in the southern lobe, but the lack of pronounced strengthening of continuous spectrum immediately contiguous to the star in the northern lobe suggests that the latter

star may be responsible for part at least of the emission spectrum. The enhanced α Cygni type of stellar spectrum is so unique that unusual properties may be suggested for such stars without prejudice to the existing data. If the star, B.D. $-22°4510$, does produce some emission luminosity in the Trifid, then α Cygni can be considered a possible source of illumination in N.G.C. 7000.

α Cygni is some 5.5 magnitudes brighter than B.D. $-22°4510$; hence, if we assume the same absolute magnitude for both stars, α Cygni would have equal illuminating powers at about thirteen times the angular distance, or by figuring from the dimensions of the Trifid, to just under 2°. The nebulosity in N.G.C. 7000 actually does extend from 2°.5 to 3°.5 from α Cygni so that, disregarding inclinations to the line of sight, and remembering that nebulosity need not be similarly distributed in these objects, we can regard the distances in the two cases as roughly of the same order. It is necessary to emphasize that this discussion does not explain the luminosity of N.G.C. 7000, and that it does not even make out a strong case. The most that can be said is that a possibility is offered which derives some weight from analogy and which must receive some consideration before it can be definitely dismissed.

Nos. 26 and 27, N.G.C. 6960 and 6992, are portions of an enormous loop in Cygnus. This nebula apparently is the one absolute exception to the suggestion that all galactic nebulae have associated with them stars of spectral types conformable to the type of nebular spectrum. The spectrum of the loop in Cygnus appears to be almost purely emission, yet no stars earlier than $B3$ nor any stars of the enhanced α Cygni type can be located, which have any probable connection with the nebula. In fact no stars at all, brighter than 9.5 magnitude, can be suggested as associated with the nebulosity.

This discussion of emission nebulae indicates that seventeen out of the twenty-six objects in Table II have stars of conformable spectral types within and obviously associated with the nebulosity. Of the remaining nine objects, three give positive evidence of association with external stars, three suggest such association, two offer possibilities of association, and one seems flatly to contradict the idea of association.

Combining the results from Tables I and II there is one clear exception and three difficult or doubtful cases out of the sixty-two nebulae. Examination of an observing list of some one hundred and twenty-five extended galactic nebulae, all the known objects of this class north of $-40°$ declination, shows no other exception and only one or two doubtful cases. The evidence then, with the single clear exception of the Cygnus loop, is very strongly in favor of the view that all galactic nebulae have associated with them stars of spectral types conformable to the types of the nebular spectra.

CONCLUSIONS

The general conclusion of this discussion is that all galactic nebulae are associated with stars and that the spectra of nebulae and associated stars have a definite relation. This suggests that galactic nebular luminosity has its source in stellar radiation. The phenomena are not simply those of reflected starlight, for in general the emission spectra of nebulae do not agree with the spectra of the associated stars. The reverse is true for diffuse nebulae with continuous spectra. In these cases the reflection theory appears to offer a reasonable explanation, or at least a working basis for further investigation. The mechanism of emission luminosity will probably find its explanation in the fact that it is always associated with the very hottest types of stars.

It is very doubtful whether or not a mass of diffuse nebulosity isolated in space and with no stars involved could hold together and at the same time shine by light generated by collisions of molecules. At temperatures corresponding to intensity-distribution or width of lines in nebular spectra, the average speeds of molecules would be so high compared to the velocities of escape that the nebulosities would probably dissipate rapidly. On the other hand, if molecular speeds were sufficiently small to admit of cohesion in the mass, the nebulosity would probably be too cold to radiate light. This argument suggests that diffuse nebulosity is not intrinsically luminous, but is rendered so by external causes. The only obvious external sources of energy are the stars actually involved in or neighboring to the nebulosity, and definite relations

have now been found to exist between the radiations of such stars and nebulosity.

The resulting conception of diffuse galactic nebulae is that they are clouds of material (molecules, dust, or larger particles) illuminated by neighboring stars. The question as to whether the association is temporary or permanent can be answered by a comparison of radial velocities of stars and nebulae. Unfortunately the large majority of such stars are binaries which require a great deal of labor for determining the velocities of the systems. This is especially true of the Oe5 and Bo stars which are associated with the diffuse emission nebulae whose velocities are best determined.

The meager data available at present are indeterminant. Radial velocities are given by Campbell and Moore for six diffuse nebulae as follows:

N.G.C. 1976 (Orion)	+17.5 km
3372	+ 6.0
6514 (Trifid)	+11.0
6523 (M 8)	− 3.0
6618 (M 17)	+ 7.0

The brighter stars in N.G.C. 1976 are all binaries for which no velocities for the systems have been determined. The stars in N.G.C. 6618 are faint and no measures have been published as yet.

η Carinae, in N.G.C. 3372, gives for the hydrogen lines velocities differing from those of other emission lines. The mean of four spectrograms measured by Sanford[1] gives +33.8 km for hydrogen and −22.8 km for the other emission lines. It is just possible that the mean, +5.5 km, may have a significance when compared to the nebular velocity, +6.0 km.

The three brightest stars in N.G.C. 6514 have been observed at Mount Wilson. They are:

B.D. −22°4150, A3p ..... − 1.5 km, 3 plates
B.D. −23°13804 (brightest comp.), Oe5 ... − 4.7 km, 4 plates, range 26 km
B.D. −23°13804 (second brightest comp.), B1 + 17.3 km, 3 plates, range 20 km
Mean ..... + 2.9 km

The two brightest components of B.D. −23°13804 are undoubtedly binaries and the mean of the seven measures for the

[1] *Lick Observatory Bulletins*, **8**, 134, 1916.

two, +6.3 km, is suggestive, but by no means conclusive, on the question of agreement between stellar and nebular velocities. B.D.−22°4510 is definitely not in agreement. Its high color-excess[1] may mean that it is seen through the entire nebula.

One star in N.G.C. 6523 has been measured—Boss 4560, Oe5, magnitude 6.1. The spectrograms give a velocity of +12.6 km. As the range is 33 km, the star must be considered a binary.

Further data on this question are very desirable. A casual inspection of diffuse nebular structure and configurations of involved stars suggests that the association is for the most part temporary. This may be one fundamental distinction between diffuse nebulae and planetaries, for in the latter the central stars must be permanently associated with the surrounding nebulosity; otherwise their central positions could not in general be maintained.

MOUNT WILSON OBSERVATORY
May 1922

[1] The color-index is 0.8 magnitudes. See *Mt. Wilson Contr.*, No. 187, p. 15; *Astrophysical Journal*, **52**, 22, 1920.

INVESTIGATIONS ON PROPER MOTION

SEVENTH PAPER: INTERNAL MOTION IN THE SPIRAL NEBULA N.G.C. 2403[1]

By ADRIAAN VAN MAANEN

ABSTRACT

Spiral nebula N.G.C. 2403.—Two pairs of plates covering eleven- and eight-year intervals, respectively, and all taken at the primary focus of the 60-inch reflector, were measured with the stereocomparator, and the motions of 76 points, presumably belonging to the nebula, were derived with respect to the mean motion of 24 comparison stars. The results for each point and star are shown by arrows on the accompanying *photograph*. *The proper motion of the nebula* as a whole comes out very small, namely, $\mu_\alpha = +0''.002$ and $\mu_\delta = 0''.000$. Taking the *inclination of the plane of the nebula* to the surface of the celestial sphere to be 48°, the *internal proper motions* in the plane of the nebula come out very similar to those found previously for M 33, 51, 81, and 101. The radial components are practically equal to the tangential components, both increasing with the distance from the center; the motions indicate an outward streaming along the spiral arms at a rate which increases from $0''.015$ per year at $1'.4$ to $0''.040$ at $8'.9$ (the average being $0''.019$), combined with an outward transverse motion of about $0''.007$ per year.

Proper motions of 24 comparison stars were also determined with a probable error of $\pm 0''.0038$ per year. All but one or two have velocities less than $0''.02$ per year.

In January, 1921, Mr. Duncan succeeded in securing with the 60-inch Mount Wilson reflector several plates of the spiral nebula N.G.C. 2403 with exposure times ranging from one hour to four hours. For this object Mr. Ritchey had already taken plates in 1910, 1916, and 1917, and Mr. Pease had taken a photograph in 1912. Of these plates four were selected for measurement, and combined into two pairs for which the observing details are given in Table I.

TABLE I

	Date	Observer	Exposure	Quality
1	1910 Feb. 7	Ritchey	1^h	g
	1921 Jan. 4	Duncan	1^h	fg
2	1912 Nov. 8	Pease	$3\frac{1}{2}^h$	g
	1921 Jan. 5	Duncan	4^h	fg

[1] *Contributions from the Mount Wilson Observatory*, No. 242.

The nebula is described by Curtis[1] as "a bright, beautiful spiral $16' \times 10'$. No nucleus apparent; many almost stellar condensations; of the general type of M 33." As the galactic latitude is not quite 30°, we have an abundance of stars which can be used for comparison purposes.

Seventy-six points, presumably belonging to the nebula, were measured, while for comparison purposes twenty-four stars from magnitude 13.5 to 17.0 were selected.

Both pairs of plates were measured with the new stereocomparator in four positions, with the direction east, west, north, and south successively coinciding with that of the increasing readings of the micrometer screw. For each pair the two measures in right ascension and those in declination were combined into one series of displacements; these values, $M\alpha_1$, $M\alpha_2$, $M\delta_1$ and $M\delta_2$, were reduced to proper motions by equations of the form:

$$\left.\begin{aligned} M_\alpha &= a+bx+cy+dx^2+exy+fy^2+m_\alpha \\ M_\delta &= a^1+b^1x+c^1y+d^1x^2+e^1xy+f^1y^2+m_\delta, \end{aligned}\right\} \qquad (1)$$

in which a, b . . . . f^1 are the plate-constants, x and y the co-ordinates of the objects measured, and m_α and m_δ the proper motions, expressed in parts of the micrometer screw. In order to reduce these motions to annual proper motions, expressed in thousandths of a second of arc, the quantities m_α amd m_δ for the first pair of plates must be multiplied by 0.765, for the second pair by 1.022.

The plate-constants were derived by least-squares solutions from the sets of twenty-four equations of form (1) for the comparison stars. The constants thus found were substituted in the equations of conditions (1) of all the objects measured. The annual proper motions are given in the fourth, fifth, sixth, and seventh columns of Table II. The second and third columns of this table contain the co-ordinates in x and y, expressed in minutes of arc, with a precision sufficient for identification.

Weights 2 and 1 were assigned to the two pairs respectively; the mean motions thus derived for the nebular points include the motion of the nebula as a whole with respect to the 24 comparison

[1] *Lick Observatory Publications*, **13**, 24, 1918.

TABLE II

Co-ordinates and Annual Displacements

No.	x	y	$\mu_{\alpha 1}$	$\mu_{\alpha 2}$	$\mu_{\delta 1}$	$\mu_{\delta 2}$
a	−6′.7	+0′.9	+0″.003	+0″.007	−0″.005	+0″.003
b	−4.8	+4.9	+ 4	+ 5	+ 21	− 7
c	−2.0	+5.2	+ 3	− 1	− 5	+ 16
d	−2.4	+3.6	− 6	+ 14	− 40	− 27
e	−2.8	+1.7	− 7	− 34	+ 3	− 6
f	−4.1	−0.3	− 4	− 6	+ 10	+ 11
g	−4.9	−1.5	+ 5	+ 6	+ 6	+ 17
h	−5.1	−4.3	+ 2	− 10	− 5	− 8
i	−3.2	−4.9	− 2	− 5	− 3	+ 8
j	−1.9	−4.4	− 6	+ 2	− 5	− 10
k	−1.6	−2.0	− 2	+ 2	+ 5	− 10
l	−2.4	−1.2	− 4	+ 11	− 3	− 13
m	−0.4	−2.1	+ 5	+ 16	+ 10	− 3
n	−0.5	−1.2	+ 14	+ 7	0	+ 6
o	+0.9	−1.8	+ 1	− 6	+ 11	− 5
p	+3.6	−5.0	+ 8	+ 19	+ 6	0
q	+4.5	−4.7	− 7	− 10	− 5	+ 2
r	+5.4	−2.5	− 3	− 3	− 7	+ 3
s	+5.9	−1.6	+ 2	− 13	− 1	+ 1
t	+4.5	+0.7	+ 5	− 9	− 10	− 3
u	+5.5	+2.4	− 2	+ 17	+ 5	− 9
v	+1.9	−0.2	− 5	− 8	− 1	+ 23
w	+3.8	+4.1	+ 1	+ 12	+ 5	− 5
x	+0.6	+5.7	− 2	− 13	+ 5	+ 14
1	−7.0	−0.3	− 20	− 42	+ 26	+ 2
2	−7.0	−0.6	− 36	− 36	+ 24	+ 29
3	−2.8	+2.8	+ 7	− 28	+ 17	+ 5
4	−2.8	+2.7	− 18	− 15	+ 13	− 19
5	−2.8	+2.6	+ 17	− 11	+ 18	+ 29
6	−2.7	+2.7	+ 8	+ 3	+ 32	+ 63
7	−2.5	+3.0	+ 5	+ 13	+ 18	+ 13
8	−3.6	+1.2	0	− 11	+ 27	+ 26
9	−3.2	+0.9	+ 2	− 4	+ 14	− 22
10	−2.9	+0.6	− 19	− 28	− 1	+ 6
11	−2.3	−2.3	− 19	− 13	+ 9	+ 7
12	−2.0	−0.8	− 2	− 16	+ 26	− 11
13	−1.9	−0.4	− 32	− 37	+ 18	+ 34
14	−1.7	−0.4	− 3	− 30	+ 7	+ 23
15	−1.4	+0.4	− 7	− 23	+ 15	− 5
16	−1.9	+0.8	− 8	− 32	+ 8	0
17	−1.6	+1.7	+ 11	+ 18	+ 28	− 10
18	−1.6	+1.8	+ 20	− 1	+ 42	+ 10
19	−1.4	+1.8	+ 22	− 3	+ 8	+ 22
20	−1.6	+2.6	+ 18	− 9	+ 28	+ 4
21	−1.7	+2.7	+ 6	+ 23	+ 22	+ 44
22	−1.2	+3.3	+ 19	+ 11	− 1	− 6
23	−0.1	+5.0	+ 8	+ 41	+ 17	+ 4
24	−0.6	+3.7	− 1	+ 19	+ 8	− 20
25	−0.4	+3.6	+ 8	− 19	+ 56	+ 8
26	−0.4	+1.8	+ 16	+ 26	+ 28	+ 7
27	−0.5	+1.5	0	+ 32	+ 4	+ 8
28	−0.2	+1.7	+ 14	+ 12	+ 12	− 30

TABLE II—*Continued*

No.	x	y	$\mu_{\alpha 1}$	$\mu_{\alpha 2}$	$\mu_{\delta 1}$	$\mu_{\delta 2}$
29	−0.″1	+1.″7	+0.″021	+0.″018	+0.″015	−0.″002
30	0.0	+1.7	+ 7	+ 39	+ 14	− 17
31	−0.3	+0.7	+ 5	+ 42	− 5	+ 6
32	−0.6	+0.8	− 15	− 32	+ 30	+ 8
33	−0.3	+0.4	+ 2	+ 22	+ 22	+ 6
34	−0.2	+0.3	+ 5	+ 17	+ 5	+ 24
35	−0.3	−0.1	− 4	+ 1	− 4	− 3
36	−0.3	−0.3	− 11	− 34	+ 2	− 21
37	−0.4	−0.5	− 18	− 24	− 3	− 40
38	−0.5	−0.9	− 6	− 13	+ 13	− 40
39	−0.7	−1.1	− 24	− 29	+ 20	− 20
40	−0.2	−1.0	+ 4	− 22	+ 1	− 29
41	−0.1	−1.2	− 5	− 22	+ 1	− 29
42	0.0	−1.2	+ 10	− 12	+ 10	− 30
43	−0.2	−1.8	− 5	− 28	+ 8	− 7
44	+1.3	−4.4	+ 4	− 16	− 8	− 21
45	+1.5	−3.5	+ 4	− 23	− 11	− 22
46	+1.3	−2.3	+ 5	− 10	− 3	− 31
47	+1.4	−2.3	− 23	+ 23	− 17	− 29
48	+2.0	−2.3	+ 16	− 30	+ 2	− 34
49	+2.1	−2.3	+ 11	+ 11	+ 1	− 10
50	+2.1	−2.2	+ 13	− 6	0	− 24
51	+2.0	−2.1	+ 4	+ 8	− 3	− 8
52	+1.5	−1.5	+ 29	− 8	− 13	− 30
53	+1.4	−1.5	+ 12	− 61	+ 7	+ 5
54	+0.9	−1.0	− 2	+ 5	− 2	− 39
55	+0.9	−0.7	+ 21	+ 4	− 5	− 19
56	+0.7	+0.4	+ 5	− 3	− 4	− 30
57	+0.6	+1.2	+ 18	+ 28	− 8	− 4
58	+1.1	+1.4	− 4	+ 9	− 15	− 38
59	+0.7	+3.7	+ 24	+ 18	+ 20	− 2
60	+0.6	+3.6	+ 28	+ 41	+ 29	− 21
61	+1.4	+0.5	+ 8	+ 16	+ 2	0
62	+1.5	+0.7	+ 17	+ 27	− 8	− 9
63	+2.1	+0.1	+ 20	− 8	− 13	− 17
64	+2.3	0.0	+ 36	− 4	− 19	− 35
65	+2.8	−0.4	+ 2	+ 31	− 1	− 21
66	+2.9	−0.5	+ 15	+ 23	− 16	− 30
67	+2.3	−0.7	+ 12	+ 30	− 3	− 72
68	+2.8	−2.4	+ 8	− 29	− 5	− 20
69	+2.7	−2.8	− 12	− 34	− 23	− 41
70	+2.9	−3.5	+ 10	− 35	+ 5	− 20
71	+2.4	−4.1	− 11	− 22	− 7	− 45
72	+2.5	−4.2	+ 2	− 12	− 8	− 61
73	+2.7	−4.1	− 3	− 23	0	− 9
74	+4.7	+2.7	+ 34	+ 31	− 10	− 16
75	+4.5	−2.3	+ 26	+ 24	0	− 46
76	+6.2	−1.8	+ 16	+ 24	− 35	− 15

stars as well as the internal motions of the individual points. To derive the motion of the nebula as a whole, the same process was followed as for the nebulae formerly discussed.[1]

[1] *Mt. Wilson Contr.*, No. 118, p. 9; *Astrophysical Journal*, 44, 218, 1916.

a) The mean for all of the 76 points gives:

$$\mu_\alpha = +0''.002 \qquad \mu_\delta = +0''.001.$$

b) If the points are divided into four groups, corresponding to the four quadrants, the means of the two groups in opposite quadrants should give a good agreement. We find:

$$\text{Means for I and III} \quad \begin{cases} \mu_\alpha = +0''.000^5 \\ \mu_\delta = -0''.001 \end{cases}$$

$$\text{Means for II and IV} \quad \begin{cases} \mu_\alpha = +0''.003^5 \\ \mu_\delta = +0''.000^5 \end{cases}$$

The four quadrants combined give:

$$\mu_\alpha = +0''.002 \qquad \mu_\delta = 0''.000.$$

c) In order to avoid points far from the center, which have an asymmetrical distribution, we may use only those within a radius of 4'.2. We find then:

$$\text{Means for I and III} \quad \begin{cases} \mu_\alpha = +0''.001 \\ \mu_\delta = -0''.002 \end{cases}$$

$$\text{Means for II and IV} \quad \begin{cases} \mu_\alpha = +0''.004 \\ \mu_\delta = +0''.001 \end{cases}$$

The four quadrants combined give:

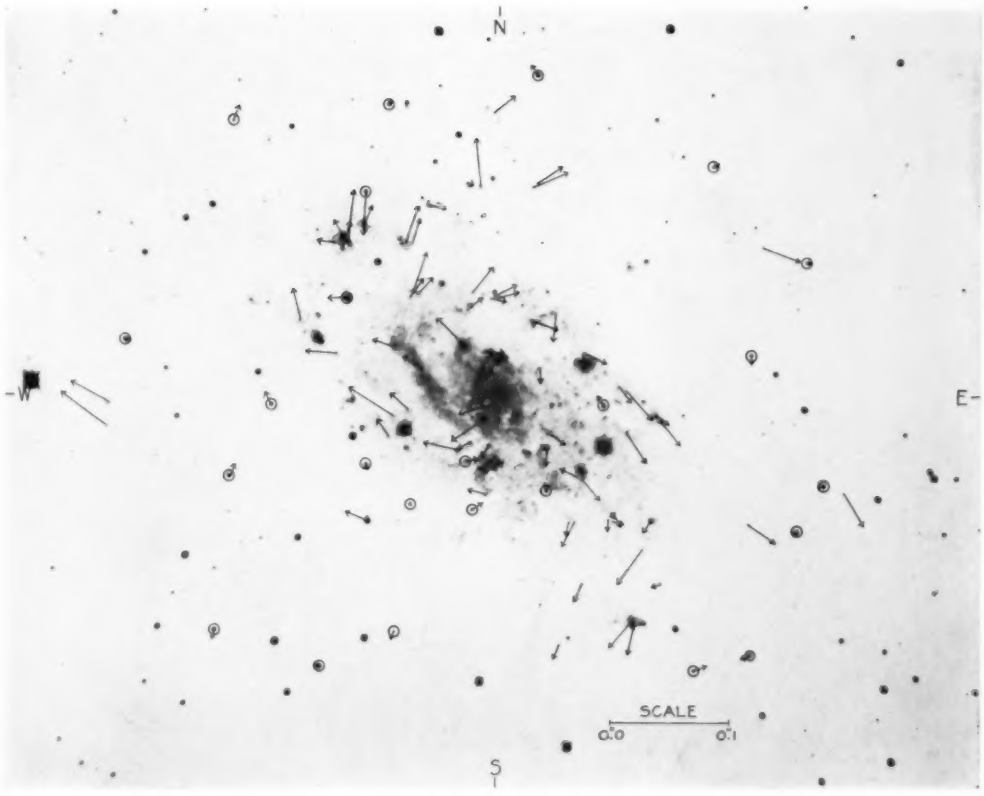
$$\mu_\alpha = +0''.002^5 \qquad \mu_\delta = -0''.000^5.$$

Giving equal weights to each of the three methods used, we derive as the final motion of the nebula as a whole:

$$\mu_\alpha = +0''.002 \qquad \mu_\delta = 0''.000.$$

If now we subtract these quantities from the values μ_α and μ_δ for the nebular points, we obtain results which represent the internal motions and are given in the second and third columns of Table III and plotted in Plate IV. The plate also shows the motions of the 24 comparison stars as given in Table II; these stars are surrounded by a circle. The scale of the motions is indicated in the lower right-hand corner. The arrows represent the motions in about 1300 years. The probable errors of the

PLATE IV



INTERNAL MOTIONS IN N.G.C. 2403

The arrows indicate the directions and magnitudes of the mean annual motions. Their scale (0".1) is indicated on the illustration. The scale of the nebula is 1 mm = 8".1. The comparison stars are inclosed in circles.

TABLE III

ANNUAL INTERNAL MOTIONS

No.	μ_α	μ_δ	Rotational	Radial	Stream	Transverse
1	−0″.029	+0″.018	+0″.022	+0″.028	+0″.034	+0″.012
2	− 38	+ 26	+ 34	+ 32	+ 46	+ 8
3	− 7	+ 13	+ 6	+ 12	+ 8	+ 10
4	− 19	+ 2	− 16	+ 12	− 10	+ 18
5	+ 6	+ 22	+ 32	+ 10	+ 32	+ 6
6	+ 4	+ 42	+ 48	+ 30	+ 52	+ 20
7	+ 6	+ 16	+ 24	+ 10	+ 24	+ 6
8	− 6	+ 27	+ 30	+ 4	+ 30	+ 4
9	− 2	+ 2	+ 2	− 2	+ 2	− 2
10	− 24	+ 1	− 6	+ 30	− 2	+ 30
11	− 19	+ 8	+ 16	+ 8	+ 16	+ 8
12	− 9	+ 14	+ 16	− 2	+ 16	− 6
13	− 36	+ 23	+ 32	+ 28	+ 38	+ 20
14	− 14	+ 12	+ 16	+ 8	+ 18	+ 4
15	− 14	+ 8	+ 2	+ 16	+ 10	+ 14
16	− 18	+ 5	− 2	+ 18	+ 6	+ 16
17	+ 11	+ 15	+ 18	+ 6	+ 20	+ 2
18	+ 11	+ 31	+ 30	+ 20	+ 34	+ 16
19	+ 12	+ 13	+ 18	+ 4	+ 20	− 2
20	+ 7	+ 20	+ 20	+ 20	+ 26	+ 14
21	+ 10	+ 29	+ 32	+ 28	+ 38	+ 20
22	+ 14	− 3	+ 20	− 4	+ 18	− 6
23	+ 17	+ 13	+ 16	+ 24	+ 20	− 22
24	+ 4	− 1	+ 6	0	+ 6	0
25	− 3	+ 40	− 4	+ 50	+ 6	+ 50
26	+ 17	+ 21	+ 24	+ 32	+ 16	+ 36
27	+ 9	+ 5	+ 14	+ 8	+ 14	+ 10
28	+ 11	− 2	+ 14	+ 2	+ 14	+ 2
29	+ 18	+ 9	+ 18	+ 20	+ 16	+ 22
30	+ 16	+ 4	+ 14	+ 16	+ 14	+ 18
31	+ 15	− 1	+ 18	+ 2	+ 18	− 2
32	− 23	+ 23	− 8	+ 26	+ 8	+ 26
33	+ 7	+ 17	+ 14	+ 16	+ 22	+ 4
34	+ 7	+ 11	+ 10	+ 14	+ 14	+ 10
35	− 4	− 4	0	+ 8	0	+ 8
36	− 21	− 6	+ 16	+ 18	+ 24	+ 10
37	− 22	− 15	+ 16	+ 34	+ 24	+ 28
38	− 10	− 5	+ 6	+ 10	+ 12	+ 4
39	− 28	+ 7	+ 24	+ 14	+ 28	− 4
40	− 7	− 9	+ 6	+ 12	+ 12	+ 6
41	− 13	− 9	+ 16	+ 16	+ 22	+ 2
42	+ 1	− 3	− 2	+ 4	+ 2	+ 6
43	− 15	+ 3	+ 16	+ 2	+ 16	− 6
44	− 5	− 12	+ 10	+ 18	+ 18	+ 10
45	− 7	− 15	+ 16	+ 18	+ 24	+ 4
46	− 2	− 12	+ 8	+ 10	+ 12	+ 6
47	− 10	− 21	+ 24	+ 16	+ 30	+ 2
48	− 1	− 10	− 2	+ 8	+ 6	+ 6
49	+ 9	− 3	+ 8	+ 8	+ 12	0
50	+ 5	− 8	− 8	+ 8	− 4	+ 12
51	+ 3	− 5	+ 4	+ 10	+ 10	+ 6
52	+ 15	− 19	+ 2	+ 22	+ 18	+ 10

TABLE III—*Continued*

No.	μ_α	μ_δ	Rotational	Radial	Stream	Transverse
53	−0″.014	+0″.006	−0″.008	+0″.016	−0″.006	−0″.016
54	− 2	− 14	+ 16	+ 8	+ 16	− 8
55	+ 13	− 10	− 2	+ 16	+ 10	+ 12
56	0	− 13	+ 14	− 12	+ 10	− 16
57	+ 19	− 7	+ 22	+ 10	+ 22	+ 10
58	− 2	− 23	+ 14	− 30	+ 12	− 30
59	+ 20	+ 13	+ 18	+ 30	+ 24	+ 26
60	+ 30	+ 12	+ 28	+ 36	+ 32	+ 32
61	+ 9	+ 1	+ 4	+ 12	+ 6	+ 10
62	+ 18	− 8	+ 16	+ 16	+ 22	+ 10
63	+ 9	− 14	+ 14	+ 4	+ 14	− 4
64	+ 21	− 24	+ 26	+ 16	+ 30	− 2
65	+ 10	− 8	+ 6	+ 10	+ 12	+ 4
66	+ 16	− 21	+ 20	+ 14	+ 24	− 2
67	+ 16	− 26	+ 26	+ 18	+ 30	− 4
68	− 6	− 10	+ 16	+ 2	+ 14	− 6
69	− 21	− 29	+ 50	+ 10	+ 48	− 16
70	− 7	− 3	+ 12	0	+ 10	− 6
71	− 17	− 20	+ 36	+ 18	+ 40	− 2
72	− 5	− 26	+ 26	+ 24	+ 36	+ 6
73	− 12	− 3	+ 16	0	+ 14	− 8
74	+ 31	− 12	+ 26	+ 26	+ 30	+ 20
75	+ 23	− 15	− 4	+ 30	+ 26	+ 14
76	+ 17	− 28	+ 28	+ 20	+ 34	0

mean annual motions for the comparison stars are 0″.0036 in α and 0″.0039 in δ; for the nebular points, 0″.0071 in α and 0″.0082 in δ.

The plate indicates motions analogous to those found for M 101, 33, 51, and 81. They may be interpreted either as a rotation combined with a radial motion outward, or as a motion along the streamers outward. In order to investigate this it is necessary to take into account the inclination of the plane of the nebula to the tangential plane of the celestial sphere. It was estimated that the intersection of the two planes is in position angle 130° and that the inclination is about 48°. A diagram was constructed in which the foreshortening of the nebula was corrected; the motions in this diagram were then resolved into (*a*) rotational and radial components; (*b*) components along and perpendicular to the arms of the spiral (stream and transverse components). The results for the individual points derived from the diagram are in the last four columns of Table III, where the positive sign is used for motions in the direction north, east, south, west, and outward.

a) The mean rotational component is $+0''.015 \pm 0''.001$; the mean radial component, $+0''.014 \pm 0''.001$. There seems, however, to be a considerable increase of the motions with distance from the center; we have:

r	$\mu_{rot.}$	$\mu_{rad.}$	n
$1'.4$	$+0''.011$	$+0''.013$	23
3.1	+0.015	+0.011	37
5.1	+0.015	+0.019	11
7.3	+0.023	+0.023	3
8.9	+0.028	+0.030	2

The rotational components would correspond to hypothetical periods of from 50,000 to 120,000 years.

b) The mean stream component is $+0''.019 \pm 0''.001$, with a transverse component $+0''.007 \pm 0''.001$. With increasing distances from the center we find:

r	$\mu_{stream.}$	$\mu_{trans.}$	n
$1'.4$	$+0''.015$	$+0''.009$	23
3.1	+0.019	+0.004	37
5.1	+0.021	+0.012	11
7.3	+0.028	−0.001	3
8.9	+0.040	+0.010	2

The evidence is then, as in the cases of M 33, 51, 81, and 101, more in favor of a motion along the streamers of the spiral, combined with some radial motion outward, than of a rotational motion.

I wish to express my thanks to Messrs. Ritchey, Pease, and Duncan, who secured the plates used, and to Mrs. Marsh, of the Computing Division, for making all the necessary duplicate computations.

MOUNT WILSON OBSERVATORY
May 1922

INVESTIGATIONS ON PROPER MOTION

EIGHTH PAPER: INTERNAL MOTION IN THE SPIRAL NEBULA M 94=N.G.C. 4736[1]

By ADRIAAN VAN MAANEN

ABSTRACT

Spiral nebula M 94 (N.G.C. 4736).—This beautiful object has a large nucleus surrounded by many closely packed whorls. Comparison of two plates taken in 1912 and 1921 by Pease and Duncan, respectively, gives an annual *proper motion* of the nebula with respect to 14 comparison stars, of $\mu_\alpha = -0''.014$, $\mu_\delta = 0''.000$. The motions of 32 nebular points with reference to the nebula are shown on the *photograph*, Plate V. The *internal motion* seems to be a stream motion of $0''.021$ outward along the arms of the spiral, combined with an outward transverse motion of about $0''.009$. The motion is analogous to that found for M 33, 51, 81 and 101 and for N.G.C. 2403.

Parallaxes of spiral nebulae.—A discussion of the methods of derivation leads to the conclusion that the three most reliable are: (1) Jeans's filament method, (2) comparison of proper motions and radial velocities, and (3) comparison of internal proper motions and spectroscopic velocities. These methods point to *parallaxes* of from $0''.0001$ to $0''.0010$ and indicate that the distances and sizes of the nebulae are considerably less than those required by the island universe theory.

Curtis[2] describes this nebula as "a beautiful object. From the very bright, large nucleus spring many bright, closely packed whorls, forming a bright inner oval $2' \times 1'.5$ in p. a. about 110°. These inner whorls show many stellar condensations, whose sharpness and proximity to the nucleus would seem to make this one of the most favorable examples known for the investigation of motion in spirals. Fainter, closely packed, rather uniform outer whorls bring the nebula to a size of $5' \times 3'.5$."

Three plates of this field were available for measurement, taken in 1912, 1916, and 1921. The first plate, secured by Pease, February 20, 1912, with an exposure of 3^h45^m was compared with the one taken by Duncan on January 5, 1921, with an exposure of 2^h10^m. Fifteen stars of photograph c magnitude 15.5 to 17.7 were selected for comparison purposes. One of these stars, *b*, was omitted in the reductions, as it showed a considerable proper motion; this star is a double having a companion of about the eighteenth magnitude at a distance of $\pm 5''$ in $p = \pm 355°$.

[1] *Contributions from the Mount Wilson Observatory*, No. 243.

[2] *Lick Observatory Publications*, **13**, 33, 1918.

Thirty-two points presumably belonging to the nebula had measurable images on the plates; 19 of these belong to the inner whorls, while 13 are at greater distances from the center. Table I gives

TABLE I

CO-ORDINATES AND MEASURED ANNUAL DISPLACEMENTS

No.	x	y	μ_α	μ_δ
a	−4.′0	+5.′7	+0.″008	+0.″004
b	−4.8	+2.6	+ 59	− 118
c	−0.8	+3.0	0	− 14
d	−1.1	+2.7	− 12	− 6
e	−6.5	−1.8	− 10	− 3
f	−5.6	−2.9	+ 4	+ 5
g	−2.9	−2.7	+ 5	+ 8
h	−0.6	−3.3	+ 3	− 12
i	+1.6	−5.5	+ 8	− 3
j	+3.5	−4.5	− 18	+ 5
k	+8.2	−1.0	+ 1	+ 4
l	+2.8	−1.2	+ 12	+ 6
m	+6.6	+2.7	+ 8	− 20
n	+4.9	+4.7	− 3	+ 3
o	+3.0	+3.2	− 7	+ 26
1	−0.7	+0.6	+ 26	+ 9
2	−0.6	+0.6	+ 12	+ 3
3	−0.6	+0.4	− 34	+ 24
4	−0.6	+0.2	− 28	+ 28
5	−1.6	+0.4	− 49	+ 31
6	−1.9	−0.9	− 53	+ 11
7	−1.3	−0.9	− 70	+ 17
8	−0.9	−1.3	− 24	+ 20
9	−0.6	−1.5	− 50	− 6
10	−0.6	−0.1	− 26	+ 14
11	−0.1	−0.4	− 44	− 12
12	−0.2	−0.6	− 32	+ 4
13	+0.1	−0.5	− 19	− 3
14	0.0	−0.6	− 35	+ 18
15	+0.4	−0.5	− 41	− 21
16	+0.4	−0.6	− 34	− 28
17	+0.5	−0.8	− 24	− 30
18	+0.9	−0.6	+ 12	− 7
19	+0.8	−0.6	− 12	+ 9
20	+2.3	−1.1	− 3	− 30
21	+2.2	−0.8	− 7	− 8
22	+2.0	−0.6	− 10	+ 4
23	+0.9	+0.2	+ 3	+ 1
24	+0.7	+0.3	+ 24	− 19
25	+0.5	+0.5	− 7	− 12
26	+0.3	+0.6	+ 39	− 6
27	−0.1	+0.7	− 11	− 1
28	+1.0	+1.4	− 16	− 3
29	+0.7	+1.4	+ 16	+ 18
30	+3.0	+1.8	− 6	− 32
31	+2.0	+1.1	+ 31	− 6
32	0.′0	−1.′6	−0.″057	+0.″010

the position and the annual motions in right-ascension and declination of the objects measured. The results were obtained in the same way as for the spirals discussed in earlier papers.[1]

The measures were as a whole rather difficult; the exposures were too long to prevent the points in the inner whorls from showing large images imbedded in much nebulosity; on the other hand the exposures were too short to give strong enough images of the points in the outer whorls.

As in all other cases previously discussed, the motions thus found are relative to the comparison stars. In order to derive the internal motions the results must be freed from the total motion of the nebula. We have therefore followed the same process as for M 101, 33, 51, 81, and N.G.C. 2403.

All 32 points give for the mean motion of the nebula:

$$\mu_\alpha = -0''.015 \qquad \mu_\delta = 0''.000.$$

Dividing the points according to the four quadrants, we have:

Means for I and III,

$$\mu_\alpha = -0''.016^5 \qquad \mu_\delta = +0''.000^5.$$

Means for II and IV,

$$\mu_\alpha = -0''.014^5 \qquad \mu = +0''.001.$$

The four quadrants combined give:

$$\mu_\alpha = -0''.015^5 \qquad \mu_\delta = +0''.001.$$

Using only the 19 points of the inner whorls, we find:

Means for I and III

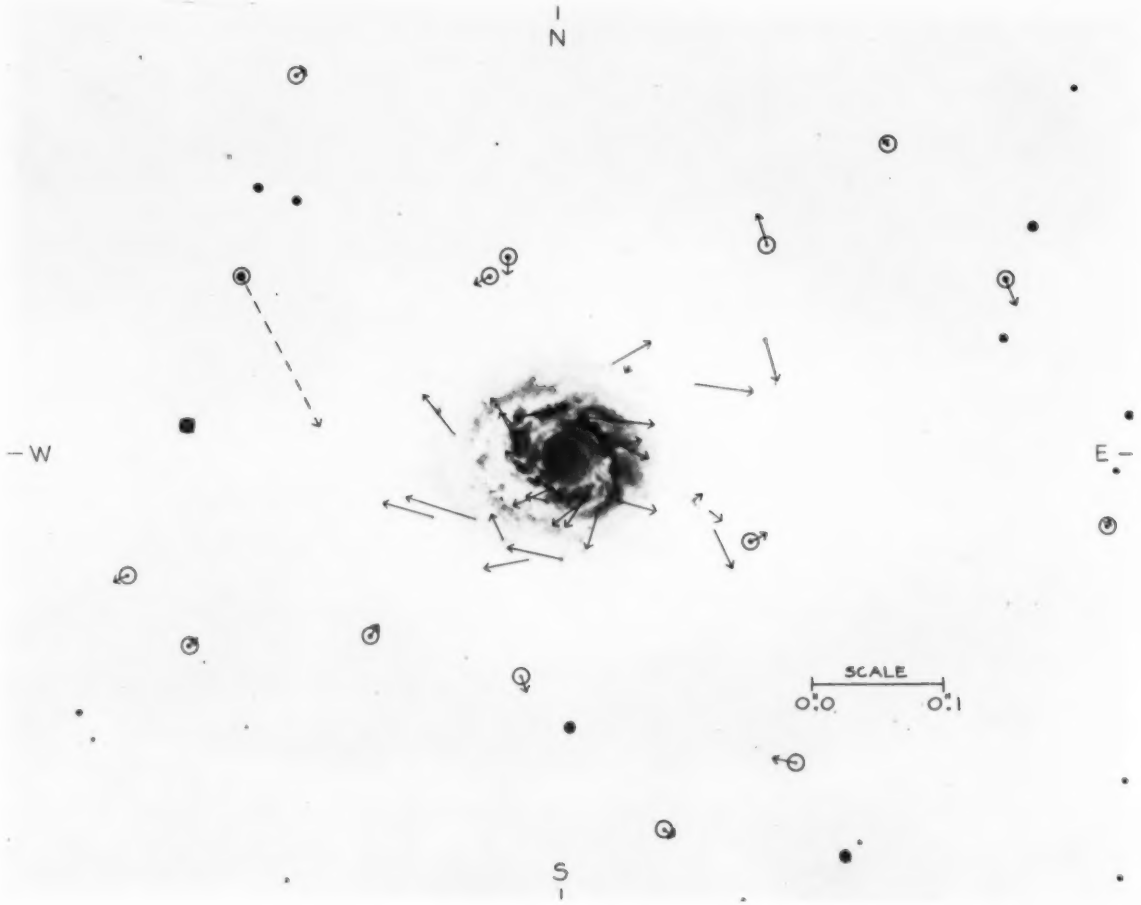
$$\mu_\alpha = -0''.009^5 \qquad \mu_\delta = -0''.001^5.$$

Means for II and IV

$$\mu_\alpha = -0''.013^5 \qquad \mu_\delta = 0''.000.$$

[1] *Mt. Wilson Contr.*, No. 118; *Astrophysical Journal*, **44**, 210, 1916; *Mt. Wilson Contr.*, No. 213; *Astrophysical Journal*, **54**, 237, 1921; *Mt. Wilson Contr.*, No. 214; *Astrophysical Journal*, **54**, 347, 1921; *Mt. Wilson Contr.*, No. 242; *Astrophysical Journal*, **56**, 200, 1922.

PLATE V



INTERNAL MOTIONS IN N.G.C. 4736

The arrows indicate the directions and magnitudes of the annual motions. Their scale (0".1) is indicated on the illustration. The scale of the nebula is 1 mm = 6".7. The comparison stars are inclosed in circles.

The four quadrants combined give:

$$\mu_\alpha = -0''.011^5 \qquad \mu_\delta = -0''.001.$$

Giving equal weights to each of the three methods, we derive as the final motion of the nebula as a whole:

$$\mu_\alpha = -0''.014 \qquad \mu_\delta = 0''.000.$$

If now we subtract these quantities from the values μ_α and μ_δ for the nebular points, we obtain results which represent the internal motions. These are given in the second and third columns of Table II and plotted in Plate V. The plate also shows the motions of the 15 stars as given in Table I; the stars are surrounded by

TABLE II

ANNUAL INTERNAL MOTIONS

No.	μ_α	μ_δ	Rotational	Radial	Stream	Transverse
1	+0".040	+0".009	+0".033	−0".026	+0".037	−0".020
2	+ 26	+ 3	+ 23	− 15	+ 23	− 14
3	− 20	+ 24	+ 10	+ 29	+ 19	+ 24
4	− 14	+ 28	+ 22	+ 22	+ 26	+ 13
5	− 35	+ 31	+ 24	+ 39	+ 27	+ 37
6	− 39	+ 11	+ 24	+ 31	+ 30	+ 26
7	− 56	+ 17	+ 43	+ 38	+ 47	+ 33
8	− 10	+ 20	+ 20	− 10	+ 17	− 14
9	− 36	− 6	+ 30	+ 19	+ 31	+ 17
10	− 12	+ 14	+ 15	+ 9	+ 16	+ 7
11	− 30	− 12	+ 19	+ 25	+ 25	+ 18
12	− 18	+ 4	+ 17	+ 3	+ 17	0
13	− 5	− 3	+ 4	+ 3	+ 3	+ 4
14	− 21	+ 18	+ 21	− 17	+ 21	− 17
15	− 27	− 21	+ 33	+ 6	+ 31	+ 12
16	− 20	− 28	+ 32	+ 11	+ 30	+ 15
17	− 10	− 30	+ 24	+ 20	+ 23	+ 21
18	+ 26	− 7	− 10	+ 26	− 13	+ 25
19	+ 2	+ 9	− 9	− 3	− 9	− 1
20	+ 11	− 30	+ 21	+ 24	+ 24	+ 21
21	+ 7	− 8	+ 5	+ 10	+ 8	+ 8
22	+ 4	+ 4	− 5	+ 3	− 4	+ 5
23	+ 17	+ 1	+ 5	+ 17	+ 6	+ 17
24	+ 38	− 19	+ 34	+ 27	+ 33	+ 28
25	+ 7	− 12	+ 13	− 7	+ 14	− 3
26	+ 53	− 6	+ 53	+ 12	+ 54	0
27	+ 3	− 1	+ 3	− 3	+ 3	− 2
28	− 2	− 3	0	− 4	− 1	− 4
29	+ 30	+ 18	+ 19	+ 29	+ 27	+ 20
30	+ 8	− 32	+ 31	− 12	+ 29	− 16
31	+ 45	− 6	+ 28	+ 37	+ 32	+ 33
32	−0".043	+0".010	+0".042	−0".010	+0".041	−0".012

The arrows indicate the directions and magnitudes of the annual motions. Their scale (0".1) is indicated on the illustration. The scale of the nebula is 1 mm = 6".7. The comparison stars are inclosed in circles.

circles; the motion of star *b*, which was excluded for comparison purposes on account of its considerable proper motion, is indicated by a broken line. The scale of the motions is indicated in the lower right-hand corner of the plate.

The internal motions were then resolved into: (*a*) rotational and radial components; (*b*) components along and at right angles to the spiral arms (stream and transverse components).

The results are given in the fourth, fifth, sixth, and seventh columns of Table II.

a) The mean rotational component is $+0''.020 \pm 0''.002$, the mean radial component, $+0''.010 \pm 0''.002$. For the points belonging to the inner whorls, with a mean distance from the center $r = 0'.7$, the values are

$$\mu_{\text{rot.}} = +0''.018 \qquad \mu_{\text{rad.}} = +0''.007.$$

For those in the outer whorls, ($r = 2'.0$) we have

$$\mu_{\text{rot.}} = +0''.022 \qquad \mu_{\text{rad.}} = +0''.015.$$

b) The mean stream component is $+0''.021 \pm 0''.002$, the mean transverse component, $+0''.009 \pm 0''.002$; the results for the inner and the outer whorl separately are:

Inner whorls	$\mu_{\text{stream}} = +0''.019$	$\mu_{\text{trans.}} = +0''.007$.
Outer whorls	$\mu_{\text{stream}} = +0''.024$	$\mu_{\text{trans.}} = +0''.012$.

Although in N.G.C. 4736 the whorls are so closely packed and so nearly circular that the difference between rotation and stream-motion is necessarily small, yet the latter seems to interpret the motions a little more satisfactorily than the former. Analogous results were found for the other spirals, except that the resemblance to stream-motion is considerably stronger in all cases. From the material now available it seems therefore necessary to give up the idea that the motions found represent a rotation. In my first paper on the internal motions in spirals[1] I computed from the rotatory components the possible masses for the spirals; this example has later been followed by Lundmark,[2] McLaughlin[3] and

[1] *Mt. Wilson Contr.*, No. 118, 1916; *Astrophysical Journal*, **44**, 210, 1916.

[2] *Publications Society of the Pacific*, **34**, 113, 1922.

[3] *Popular Astronomy*, **30**, 294, 1922.

others. Since now, however, it seems necessary to abandon the conception that we are dealing with rotation, we must at least for the present abstain from deriving conclusions as to the masses of the central bodies.

The problem of the distances of the spiral nebulae has been discussed by several astronomers during the last few years, principally by Curtis and Lundmark. In his exhaustive study, "The relations of the Globular Clusters and Spiral Nebulae to the Stellar System,"[1] Lundmark approaches the subject in not less than nine different ways. Some of these are based on the supposition that the spirals are comparable in size to the Milky Way system or to the Magellanic Clouds and thus start from assumptions which we are just trying to examine by deriving their distances. As examples we may quote Wolf's comparison of the caves in the Milky Way and in spiral nebulae and the hypothesis that the Magellanic Clouds are spiral nebulae. It is true that the large Magellanic Cloud resembles in appearance the nebula N.G.C. 4449, but then N.G.C. 4449 is far from a typical spiral. Curtis, for instance, describes this object as: "A very bright and interesting object, filling a space about $3'.5 \times 2'$. It is of exceedingly irregular structure, with many almost stellar condensations, and a bright nearly stellar nucleus. Of spiral type, as to nebulosity, but with very little evidence of spiral form."

Another derivation of the distances of spiral nebulae has been based on the appearance of novae in them. Assuming the absolute magnitudes of these novae to be the same as those in the Milky Way, a parallax can be derived. The assumption, however, that the novae in the Milky Way and those in the spirals have the same absolute magnitude is open to question. Of the 30 novae, more or less, which have been found in spirals, all but two (in N.G.C. 4321) appear in spirals showing a large amount of nebulosity. Attention has not before been called to this fact; why, for instance, has no nova ever been found in M 33, which resembles very much more Easton's structure of the Milky Way than does the Andromeda nebula? It is true that there exist a greater number of photographs of the Andromeda nebula; but of M 33 the Mount Wilson

[1] Dissertation, 1920. The work has been extended in several recent articles in the *Publications of the Astronomical Society of the Pacific.*

Observatory has available more than two dozen plates, all of which have been examined, principally by Messrs. Duncan and Humason, yet not a single nova has been found, while in the Andromeda nebula one in every two or three plates shows the image of a nova.

Of the other ways of determining the parallaxes of the spiral nebulae, the following may be mentioned.

a) The direct determinations seem to be unsatisfactory; the parallaxes derived by Barnard for the Andromeda nebula and by van Maanen for three spirals indicate that their parallaxes are smaller than the probable errors. This point might have been omitted if Bohlin[1] had not recently called attention to the large parallax derived by him for the Andromeda nebula, for which Barnard found $\pi = 0''.000$ and van Maanen $+0''.004$. Bohlin's measures are based on plates with the 6-inch Steinheil objective of the Stockholm Observatory, and it is well known from the researches of Kapteyn and others, that on plates taken with the smaller instruments, systematic errors of considerable size appear, especially if the hour-angles are large.

b) Star counts by Lundmark in the region of the Andromeda nebula show an increase of stars near the center; in M 33 there is no indication of an increase or a decrease in the number of stars as we approach the center of the plate. Lundmark concludes that these two spirals do not seem to absorb the light of stars as faint as magnitudes 16.5 and 15.7, respectively, and derives as a minimum parallax $0''.000360$ and $0''.000498$, respectively.

c) An ingenious method of determining the parallaxes of spiral nebulae was proposed by Jeans.[2] It is based on the conditions necessary for the breaking up of the line elements of the filaments thrown off by the nucleus. For M 101 Jeans thus derives a parallax of $0''.001$. Although no great stress should be laid on this figure, it gives an indication of the order of magnitude of the distances.

d) Curtis has derived the proper motions of many of the spirals for which plates had been taken at the Lick Observatory. In his later papers, he does not use these motions, on the supposition that they are not real motions but due to the accidental errors of

[1] *Jubiläums Nummer, Astronomische Nachrichten*, 1921.

[2] *Problems of Cosmogeny and Stellar Dynamics*, p. 217 (1919).

the measures. Lately, however, Lundmark has derived the motions of several spiral nebulae from the positions given in several catalogues. Comparing his motions with those of Curtis, I find, after the necessary corrections for a systematic difference, that they agree in sign in 62 per cent of the cases. As, moreover, the twelve values derived by van Maanen show an agreement in sign with Curtis' values in not less than 75 per cent of the cases, we must come to the conclusion that Curtis' results are not altogether due to the influence of accidental errors. Another point shows this too; from the radial velocities we find a relation between the size of the spirals and their motion, the smaller spirals having the larger motions. The results are given in the second column of Table III, while the third column gives the number of objects included. As we find an analogous relation for the proper motions, which are given in the fourth column, we must conclude that these are at least partly real.

TABLE III

Diameter	V	n	$\bar{\mu}$	n'
	km/sec.			
$>10'$	339	5	0".031	6
$5'-10'$	474	9	0.032	10
$<5'$	826	10	0.041	13

If then we use Curtis' mean motion of 0".033 for the 66 largest spirals, and compare this value with the mean radial velocity, we derive a mean parallax of 0".0003. Dr. Lundmark, who has recently computed the apices and mean parallaxes derived from Curtis' and his own proper motions, kindly allows me to mention his result in advance of publication. Using 800 km/sec. for Campbell's K-term in the solution he finds:

Mean parallax from 67 motions derived by Curtis, 0".00010
Mean parallax from 82 motions derived by Lundmark, 0".00011

The value of K is as yet very uncertain; smaller values of K will give larger parallaxes, and vice versa.

e) Finally we may compare the internal motions found by van Maanen with those derived by spectroscopic means; these

amount to a few hundred kilometers per second; the comparison yields parallaxes of a few ten-thousandths of a second of arc, giving for the diameters of the spirals quantities from 10 to 300 light years.

Of the methods mentioned above, those under *c*, *d*, and *e* probably deserve the most credit. This material does not seem to warrant the acceptance of the island-universe theory. It is of course possible that later results may contradict this statement; but it seems well to point out that the evidence based on the best material at present available does not indicate that the spiral nebulae are comparable with our Milky Way system.

MOUNT WILSON OBSERVATORY
June 9, 1922

CORRIGENDA

ASTROPHYSICAL JOURNAL, **56.**

Page 129, Table I, column 6, line 6:
For 22,518.6 *read* 22,528.6.

Page 130, line 8 from bottom:
For initial energy *read* potential energy.